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Dynamic Modelling of a Linear Friction Welding Machine Actuation System for Fault Detection and Prediction

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DYNAMIC MODELLING OF A LINEAR FRICTION WELDING MACHINE ACTUATION SYSTEM FOR FAULT DETECTION AND PREDICTION

Submitted by

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Abstract

Linear Friction Welding (LFW) is a relatively new process adopted by aircraft engine manufacturers utilising new technologies to produce better value components. With increasing fuel prices and economical drives for reducing CO_2 emissions, LFW has been a key technology in recent years for aircraft engine manufacture in both commercial and military market sectors. For joining Blades to Discs ('Blisks'), LFW is the ideal process as it is a solid state process which gives reproducibility and high quality bonds therefore improving performance. The welding process is also more cost effective than machining Blisks from solid billets, and a reduction in weight can also be achieved with the use of hollow blades. The LFW process also allows dissimilar materials to be joined and a reduction in assembly time.

The main aim of the research is to create a simulation model of a Linear Friction Welding machine and also apply systems thinking to fully understand the LFW process with a view to reduce total production costs. As this EngD focuses on systems thinking, a holistic approach will be used. The hard systems parts of this project will involve the mechanics of the system and understanding relationships between the key system interactions during the welding process in order to create an analytical model of the machine to use for fault diagnosis and prediction. The soft systems parts will focus on the machine users to gain an understanding of how to effectively implement the model with the process and its users.

The benefits of the new model include the ability to execute it in a real- time environment with machine operation, allowing weld anomalies to be detected as (and in some cases before) they occur, as well as the monitoring of the machine's condition. Therefore the business benefits would be realised through a reduction in machine downtime enabling the timely supply of goods providing customer value. Further benefits will be the greater understanding of the complex operation of the whole system and the welding process.

Developing a robust research investigation framework, a research hypothesis is introduced and subsequent research questions are developed. Through a combination of hard system investigation using mathematical modelling and soft systems understanding through an action case study intervention, a holistic model is developed.

Acknowledgements

I would like to thank all who supported me during this research project. In particular, I am grateful to my academic supervisors Andrew Plummer, and Patrick Keogh, and my industrial supervisor Peter Wilson. Their advice and guidance throughout the project has been greatly appreciated.

The majority of my research time has been spent based at a Rolls-Royce site in Annesley, working with the LFW team, individuals such as Adrian Seal, Charlotte Gibson, Henry Reader, Graham Colin, Tony Jones, Mick Gibson, Andy Perrie, Mark Williams, and Alistair Atkinson have made my research enjoyable, but more importantly I have gained a lot of experience and knowledge from each of them.

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A special thanks to my partner Hayley, and son Kyzley for encouraging me and keeping me motivated throughout, and also to my friends and family for continuously supporting me and for always being present.

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Nomenclature

$u(t) = \ Process\ input$

$e(t) = \ Controller\ error$

$w(t) = Target\ signal$

$r(t) \ = \ Reference\ signal$

$y(t) \ = \ Output\ signal$

$w_0 and\ w_1 = \ Adjustable\ weights$

$K_p = \ Proportional\ gain$

$K_i = \ Integral\ gain$

$K_d = \ Derivative\ gain$

$Q_1 = \ Flow\ out\ of\ port\ 1\ into\ cylinder\ m^3/s$

$Q_2 = Flow\ into\ port\ 2\ from\ cylinder\ m^3/s$

$Q_{s1} = Flow\ out\ of\ port\ 1.\ For\ 2^{nd}\ stage\ valve\ m^3/s$

$Q_{s2} = Flow\ out\ of\ port\ 2.\ For\ 2^{nd}\ stage\ valve\ m^3/s$

$X = \ Spool\ movement\ mm$

$U = \ Valve\ drive\ v$

$k_v \ = \ Constant\ for\ a\ given\ valve\ and\ a\ given\ fluid\ GPa$

$X \ = \ Normalised\ spool\ position$

$P_1 \ = \ Pressure\ at\ port\ 1\ N/m^2$

$P_2 = \ Pressure\ at\ port\ 2\ N/m^2$

$P_s = \ Supply\ pressure\ N/m^2$

$P_a = \ Main\ system\ pressure\ N/m^2$

$P_r = \ Return\ pressure\ N/m^2$

$Q_R = Manufactures\ rated\ flow\ m^3/s$

$Q_B = \ Body\ flow\ m^3/s$

$A = Piston\ Area\ cm^2$

$K_1, K_2 = Fluid\ stiffness\ GPa$

$V_{t1}, V_{t2} = Fluid\ \ volume\ \ m^3$

$M = Mass\ kg$

$F = Force\ N$

$c = \ Cross\ piston\ leakage\ coefficient\ m^5/Ns$

$c_1 = \ Cross\ port\ bleed\ coefficient\ m^5/Ns$

$c_t, c_f = \ Leakage\ coefficient\ m^5/Ns$

$B = Bulk\ Modulas\ GN/m^2$

$S_f = Half\ the\ stroke\ of\ the\ spool\ mm$

$W_{ns} = \ Natural\ frequency\ rad/s$

$n = Polytropic\ index$

$r = Residual$

$u = Input\ vector$

$w = Noise\ process$

$x = State\ vector$

$y = Output\ vector$

$A = System\ matrix$

$B = Input\ matrix$

$C = Output\ matrix$

$D = Transmission\ matrix$

$G = Process\ noise\ matrix$

$H = Process\ noise\ for\ outputs\ matrix$

$v = White\ noise$

$L = Kalman\ filter\ gain$

$\hat{x} = Observer\ state\ vector$

$\hat{y} = Observer\ output\ estimate$

$A(t) = Oscillation\ amplitude$

$v(t) = Oscillation\ velocity$

Publications

(3 papers)

[P1] **Williams, D.T. Plummer, A.R. Wilson, P.** 2012. Dynamic Modelling of a Linear Friction Welding Machine Actuation System. Presented at the Bath/ASME Symposium on Fluid Power and Motion Control (FPMC'12), University of Bath on the 12th-14th September, 2012.

[P2] **Williams, D.T. Plummer, A.R. Wilson, P.** 2013. Fault Detection of a Linear Friction Welding Production System Using an Analytical Model. Presented at the Eighth International Conference on Systems (ICONS'13). Seville, Spain. Jan 27 – Feb 1, 2013.

[P3] **Williams, D.T. Beasley, R. Gibbons, P.M.** 2013. Combining hard and soft systems thinking: the development of a valve improvement model for a complex linear friction welding repetitive process (lfw-VIM). Accepted at the conference on Systems Engineering Research (CSER'13). Georgia Institute of Technology, Atlanta, Georgia March 19-22, 2013.

Chapter 1: Introduction

1.1 Background to the Research

The airline industry is continuously under threat to remain competitive in their market place and also comply with the ever changing legislation and government requirements[1]. At Rolls Royce this has directly impacted the aircraft engine manufacture. This thesis focuses on one particular process, on one particular component in the aircraft engine manufacture. Linear Friction Welding (LFW) is a relatively new process adopted by aircraft engine manufacturers utilising new technologies to produce better value components. With increasing fuel prices and economical drives for reducing CO_2 emissions, LFW has been a key technology in recent years for aircraft engine manufacture in both commercial and military market sectors. For joining Blades to Discs ('Blisks'), LFW is the ideal process as it is a solid state process which gives reproducibility and high quality bonds therefore improving performance. The welding process is also more cost effective than machining Blisks from solid billets, and a reduction in weight can also be achieved with the use of hollow blades. The LFW process also allows dissimilar materials to be joined and a reduction in assembly time.

At the heart of the LFW process is a complex electrohydraulic system controlling key process variables which can influence the weld quality and machine/process repeatability, opportunities for improving the machine monitoring process exist to enable the reduced probability of scrapping components. The main aim of the research is therefore to create a simulation model of a LFW machine in Simulink and also apply systems thinking to fully understand the human interactions. Developing a holistic model, will involve the mechanics of the system and understanding relationships between the key machine components which interact during the welding process. Users of the machine also have a big role in this project as an understanding of the model, machine, and user interactions would be crucial for successful model implementation.

[1] Plan to reduce Aviation CO2 Emissions Unveiled. As viewed 10/2012 at http://www.thejakartaglobe.com/justadded/plan-to-reduce-aviation-co2-emmisions-unvield/271240

The benefits of a model to monitor the machine and welding process would include the ability to execute it in a real- time environment with machine operation, allowing weld anomalies to be detected (fault detection) and some weld anomalies to be predicted (fault prediction), as well as the continuous monitoring of the machines condition. The detection and prediction of faults could save scrapping a component which could cost in excess of £250,000, as well as reducing the amount of disruption to production involved with unexpected machine downtime.

Therefore the business benefits would be realised through a reduction in machine downtime enabling the timely supply of goods providing customer value.

The first part of the thesis introduces a mathematical model developed to focus on understanding the machine in isolation of human intervention which can be used to detect and predict faults. This model is demonstrated through validation and a number of fault case simulations. The second part of the thesis widens the system boundary to also encompass the human elements of the process and other influencing factors such as plant condition and leadership. Taking an action case study approach, a model of understanding is developed in-situ with the process operators and management team by applying the soft system: Customer → Actors → Transformation → World View → Owner → Environment (CATWOE) modelling tool. Combing the hard and soft system elements of the model, the penultimate part of the thesis presents the adoption of a value improvement model allowing for a visualisation of the LFW repetitive process and the links between the machine system and the human interactions.

The final section of the thesis revisits the hypothesis, research questions and outlines academic contributions to the body of knowledge. Although not the main aim of the research, an additional contribution will show how systems thinking can be applied to develop a holistic model of a complex repetitive process, showing how the soft system human elements influence the hard system machine and subsequent process outcomes -a Linear Friction Welding Value Improve Model (*lfw*-VIM).

1.2 Research Hypothesis and Questions

In order to demonstrate how holistic systems thinking can be applied primarily to a hard systems thesis, the research hypothesis developed triggers research questions which enable the hard and soft systems aspects of the problem to be explored. An analytical simulation based approach, alongside an action research case study approach can be explored from the following research hypothesis:

Systems thinking can be applied to a complex Linear Friction Welding machine; in order to create an analytical model of its behaviour enabling the development of a fault detection and prediction tool alongside understanding the human–machine interactions to aid effective tool deployment at Rolls-Royce.

The research hypothesis lends itself into splitting the thesis up into two parts, one focusing on the modelling of the hard system, and the other focusing on understanding how the soft system elements interact with the hard system. Developing specific research objectives and aiding the structure of the thesis, the following list of three research questions aim to be answered:

R1: *Can an analytical model be developed to accurately represent a complex physical electro-hydraulic system?*

R2: *Can the developed tool be useful in detecting and predicting faults under production conditions?*

R3: *What considerations are needed for effective tool deployment with the machine and human interactions?*

1.3 Thesis Structure

This thesis is separated into 8 chapters, with each outlined as follows:

Chapter 2: Introduction to Systems Thinking: Understanding the Hard and Soft Systems Elements of the Project introduces the systems thinking relating to the hard and soft systems contained within this thesis. The relevant hard and soft systems literature is reviewed developing an understanding of the body of knowledge complemented by a critique discussing the strengths and weaknesses of the different approaches in relation to this research project.

Chapter 3: Research Methodology: outlines a relevant sample of research methodologies from the literature, and then justifies the use of a mixed (quantitative and qualitative) research approach.

Chapters 4 and 5 are based on a paper developed and presented by the author at the Bath/ASME Symposium on Fluid Power and Motion Control (FPMC'12), September 2012, the paper can be found in Appendix 11. Chapter 4: Modelling introduces the LFW machine to be modelled, outlines the modelling approach used, and then carries out the modelling of the machine (the LF60) for fault detection and prediction purposes. Chapter 5: Validation validates the LF60 model. The validation is done using the Normalised Root Mean Squared Error (NRMSE), Amplitude Ratio (AR) and Phase Difference (PD), to show the models accuracy when compared to the actual LF60 machine signal outputs. A subsection of the model is also validated for fault prediction purposes. The chapter closes with a discussion of research question one.

Chapter 6: Fault Detection, Isolation and Prediction is based on a paper presented at the Eighth International Conference on Systems (ICONS'13), Jan/Feb 2013, the paper can be found in Appendix 12. This chapter simulates the model with a number of fault cases to investigate the models sensitively in detecting faults, and reviews the predictive model. The second research question is discussed.

Chapter 7: Modelling – Human – Machine Understanding is based on a paper accepted at the Conference on Systems Engineering Research (CSER'13), March 2013, the paper can be found in Appendix 13. This chapter implements a Value Improvement Model, which investigates into a case study combining the hard and soft elements of this thesis, to develop a holistic understanding of the research. This chapter closes with a discussion of the third research question.

Chapter 8: Conclusion summarises the key points from the investigation and revisits the hypothesis and research questions. Contributions to the body of knowledge are presented along with further developments.

Appendices contain additional test results and papers covering this research which have been published or accepted.

Chapter 2: Introduction to Systems Thinking: Understanding the Hard and Soft Systems Elements of the Project

2.1 Introduction

Developing a robust argument in the development of a useful model for understanding the LFW process, this chapter of the thesis will review the related hard and soft systems literature. Reviewing hard and soft systems independently, an initial review will develop an understanding of the body of knowledge complemented by a critique developing an understanding of the strengths and weaknesses of the different approaches in relation to this research project.

2.2 An Holistic Viewpoint

A holistic understanding is necessary when trying to understand a complex system or process which has a level of uncertainty and the involvement of people [1]. [2] argues systems thinking allows a holistic approach to be taken therefore enabling effective action by viewing the overall picture, highlighting the links between parts.

To take a holistic view of a system the various systems thinking developments should be known which are discussed in depth in [1]. A useful map outlining the systems movement and the various system developments developed by [3] can be seen in figure 1, for the purpose of this investigation, soft and hard system developments will be explored in more detail as to their suitability for this investigation. As the research project is not looking to further the theoretical development of systems thinking, this element of Marashi's [3] model will not be discussed.

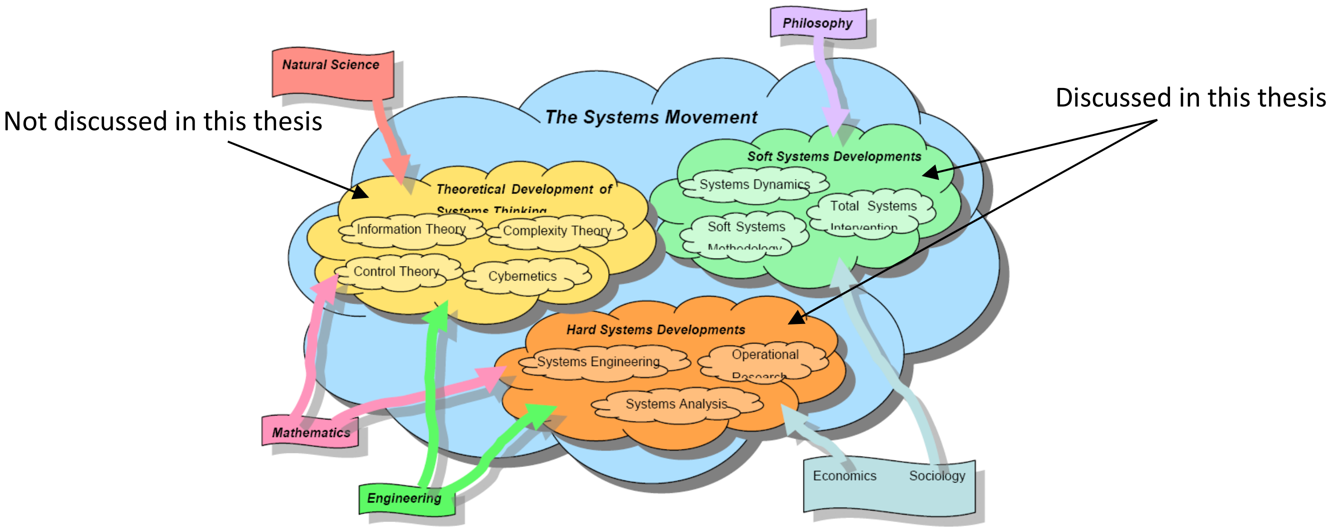

Figure 1 - The shape of the system movement indicating major influences [3]

Linking Marashi's [3] model to this research project, the hard system element relates to the modelling of the physical Linear Friction Welding system which takes the input of Blades and Discs to output Blisks, and the soft system element relates to the modelling and the human interactions surrounding the welding machine and use of the physical model.

2.3 Literature Review: Hard Systems

Hard systems approaches generally look for the answer in how to solve a problem, the problem usually stems from a system that is created to meet a set of defined objectives [1]. Jackson [1] argues that hard systems approaches generally look for the answer in how to solve a problem, with the problem usually originating from a system that is created to meet a set of defined objectives. Developing a conceptual framework, Jackson [1] proposes the usual methods of solving these problems is to develop models and explains models in hard systems thinking are designed to capture the essential features of the real world, by detailed observation, measurement, personal insight, and incomplete information to understand regularities in behaviour. Once a model has been developed it becomes useful in investigating the systems problems without affecting the actual system, therefore the accuracy of the model is crucial to portray the correct system characteristics [1].

Jackson goes onto criticise hard systems thinking methods referring to their inability to handle significant complexity, and also its inability to deal satisfactory with multiple perceptions of reality. The soft systems elements in this thesis help negate the criticism raised by [1].

A number of techniques in analysing hard systems problems exist in the literature such as Systems Analysis (SA), Systems Engineering (SE), and Operational Research (OR). SA defines the problem to be solved and provides the architecture of the proposed system [4]. SE aims to identify and manipulate the properties of a system as a whole [5]. OR can be used to create mathematical models to describe the system, simulating these models can be used to solve problems, or find improved decision-making and efficiency [6]. Mathematical modelling of the LFW machine will be done in this thesis, therefore the most appropriate hard systems method to use is the OR methods. [7] presents a useful framework for understanding the OR approach:

1. Formulating the problem;
2. Constructing a mathematical model to represent the system under study;
3. Deriving a solution from the model;
4. Testing the model and the solution derived from it;
5. Establishing controls over the solution;
6. Putting the solution to work (implementation).

The first step is primarily systems analysis, once the problem is formulated, the rest of the project should be organised with definitions and objectives of the system and its boundary, with the necessary information and data collected. Following on from that the model can be built to represent the system under study. The third and fourth steps involve deriving solutions from the model and checking these are consistent with the real system. Once model results are known and acceptable, the final two steps enable one to control the results to give useful outputs then implement the solution to give the required benefits.

Therefore the OR research method will enable the development of an analytical mathematical model used to represent the complex system characteristics and interactions that combine the Linear Friction Welding operational behaviour. The mathematical model will be classed as a non-deterministic, dynamic systems model as shown in figure 2 [8].

	Steady state	Dynamic
Deterministic	Algebraic equations	Differential equations
Non-deterministic	Statistical and probability relationships	Discrete-event simulation

Figure 2 - Types of analytic models

The hard systems in this project will take the form of an analytical model being built of the physical system; the soft systems aspects will enable a greater understanding of the hard system by including the human and environmental aspects, therefore creating a holistic approach to solving the EngD.

2.3.1 Introduction to Hydraulics: Why Hydraulics

The actuation of systems can be achieved by a variety of means, such as hydraulic, pneumatic, mechanical and electromechanical, of these electromechanical and hydraulic actuation systems are the most commonly used. [9] describes the advantages of hydraulic actuation systems as having:

- The ability to cope with high loads while reacting to a fast input response.
- Higher stiffness due to there being relatively low drop in speeds under applied loads.
- A large power-to-weight ratio – Hydraulic systems are usually made with dense materials, therefore they can delivery large mechanical energy for generally small devices.

[9] also describes the disadvantages of hydraulic systems as:

- Needing continuous maintenance, to reduce oil contamination, leaks, and other potential causes of failure.

- Having an increased complexity, therefore care is needed in their design and implementation.

- Being less flexible when compared to electric motors running at lower power levels.

Depending on the application the majority of time hydraulic methods of actuation outperform other methods, examples of hydraulic actuation systems are given in the following section.

2.3.2 Hydraulic Applications

Hydraulic systems are present in a number of industrial applications, mainly due to their fast response and large force-to-weight ratio. Systems such as active suspension systems [10], excavators, [11], presses [12], and aerospace motion control [13] all contain hydraulic actuation systems.

Modelling of hydraulic systems has been widely covered in the literature [14-17], the proceeding section reviews modelling techniques applicable to hydraulic systems.

2.3.3 Modelling

No full system dynamic modelling of linear friction welders has previously been done in the literature. Similar multi-axis machinery has been modelled such as Stewart-Gough platforms [18] which are mainly used in aerospace and automotive simulators, and shaking tables [19] used for earthquake simulations. Models of these systems are developed to enable detailed understanding of the dynamic characteristics therefore allowing control algorithms to be optimised and the systems limitations to be assessed. Modelling in this case will be done to enable detailed understanding of the systems dynamics, and for fault detection, including real-time simulations in order to detect faults before they cause production problems.

Modelling involves understanding the system and finding the most likely values for parameters, parameter estimation is usually carried out from available knowledge and data. Structural identifiability and numerical identifiability establish the type of identifiability a system has. If the model parameters can be identified from a specific input-output experiment given perfect data then this is considered structural identifiability. [20] Explains that a certain model parameter is *globally identifiable* if it is evaluated uniquely from a set of measurements, it is *locally identifiable* if it has a finite number (>1) of solutions, and it is *unidentifiable* if it has an infinite number of solutions. If the data is not perfect but real, noisy data then it is considered numerical identifiability and is essentially a problem of parameter estimation accuracy.

Different approaches to modelling complex systems have been undertaken in the past. Taylor series expansion can be applied to non-linear systems but has difficult application for the more complex systems. Linearisation of the system around a suitable operating point can be accompanied by the use of identifiability analysis of linear systems, but this can lead to modelling inaccuracies as fewer parameters will be present [20]. The LF60 is a highly non-linear system, with the non-linearity's arising from flow deadband, saturation, non-linear opening of valve orifice, friction, and the relationship between pressure and flow. Electro-hydraulic servo valves are commonly modelled by considering a time domain linear model and estimating its unknown parameters [21]. The non-linearity's make analytical methods of modelling difficult and a system identification approach to characterise the complexities of the system is necessary, techniques such as a Pseudo-Random Binary Sequence input as demonstrate in [21] is used to estimate parameters by exciting an electro hydraulic Servovalve.

There are a wide variety of estimation techniques, an extensive review can be found in [22]. [23] Uses a Matlab least-squares method to estimate an ARX model of a high performance hydraulic actuator in force control, the analytical model includes all non-linear elements and is able to predict the real systems behaviour quite well. Other hydraulic systems have been modelled in the literature, such as in [24] where Diagonal Recurrent Neural Networks (DRNN) can identify the hydraulic servo systems dynamic performance. The paper shows the results with a back propagation algorithm, and shows the simulation results which demonstrate the dynamical performance being achieved rapidly and accurately. Discussions of model parameter estimation using Monte Carlo simulation techniques can be seen in [25], where a valid model for a required use can be obtained.

Modelling studies on electro-hydraulic systems can make use of linear first-, second- or third- order difference equations [26], and then the identification of parameters can be done using a variety of linear optimisation techniques such as the least-squares algorithm.

2.3.4 Control

The LF60 uses Proportional, Integral, Derivative (PID) and Amplitude and Phase Control (APC) control to ensure high precision servo-hydraulic control. PID control due to its simplicity and usefulness is a powerful and common control method for a wide range of industry processes. The first analogue PID controllers were introduced into industry in the late 1930s by the companies Taylor Instrument, and Foxboro Instrument. These were further developed to become easily tuneable, robust, reliable digital controllers in the late 1950s [27]. The different gains of the controller perform different actions on the system as follows [28]:

Proportional (gain) adjusts the output in proportion to the current error value and is usually termed K_p which affects response speed. The Integral (reset) is proportional to both the magnitude of the error and the duration of the error termed K_i which eliminates steady state errors. Derivative (rate) affects the rate of change of the process error, by determining the slope of the error over time termed K_d which decreases overshoot.

APC control is an adaptive control technique used to modify a command signals amplitude and phase, the aim of the APC is to monitor its own performance and vary its own parameters to improve performance. For the LF60 the APC acts on the position command signal to reproduce it, therefore enabling the feedback to match the original command signal [29].

The APC processes the command signal, to eliminate any amplitude or phase differences exhibited by the feedback signal. The weights W_0 and W_1 are continuously updated at rates of 10 to 20 times the system frequency, this is to reduce the estimation error (to zero) seen by the weight adjuster which is usually a Least Mean Square (LMS) algorithm. The LMS algorithm finds the weights that produce the LMS of the estimation error by using the gradient descent method [31].

The main adjustable APC parameters are the convergent rate – used to set the speed of APC tracking correction and controls how aggressive the feedback follows the command signal, initial APC drive – an amplification factor used to set the starting gain, and initial APC phase – used to start the initial phase offset. The initial APC gain and phase are crucial in starting the correction, further details of the APC controller can be found in the patent [30].

2.3.5 Process Modelling

The main sources of thermal energy will stem from the welding process. Process modelling has been widely covered in the literature, understanding the level of high forces reached, large acceleration and decelerations, rapid dissipation of energy, material behaviour and temperatures. Linear friction welding is a self-regulating process, where its success depends on the initial process parameters used, i.e., amplitude and frequency of oscillation, and friction pressure applied and also on the amount of flash expelled [32]. An example of two test pieces, with the main welding forces outlined can be seen in figure 3.

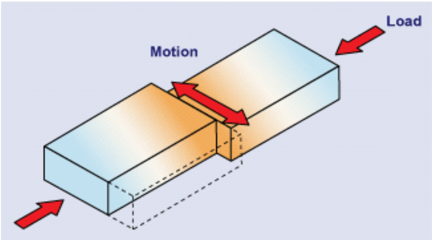

Figure 3 - Oscillating Weld Pieces

Modelling the dynamic behaviour of friction has been investigated by [33], a modified LuGre model is used to simulate the real dynamic behaviours of the friction of a hydraulic actuator with good accuracy. A LuGre model can simulate almost all the dynamic behaviours of friction such as presliding displacement, frictional lag, varying break-away force and stick-slip [34]. Previous modelling of the LF60 welding process has been done in [35], it was found that the instantaneous friction coefficient measured varied approximately linearly with blade velocity within certain boundaries. The simplified model developed gave reasonable results and therefore will be developed further to provide the process modelling of the LF60. The weld process modelling findings from [35] include the calculation of the coefficient of friction (1):

$$\frac{WeldLoad(FrictionalForce)}{NormalForce} = CoefficentofFriction \qquad (1)$$

Equation (1) agrees with Amontons 1st empirical law of sliding friction, which states that the force of friction is directly proportional to the applied load [36]. Also a relationship between the coefficient of friction and velocity is described in [35], which can be seen in figure 4:

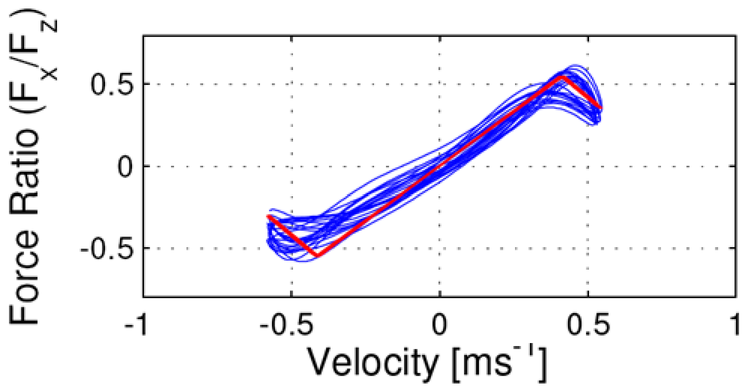

Figure 4 - Empirical relationship for weld force [35]

The friction and velocity relationship from [35] was modelled as a straight line, not taking into account the hysteresis seen. The relationship in figure 4 agrees well with [37] which describes the frictional forces vs. velocity having stick-slip and stick-sliding regions as shown in figure 5:

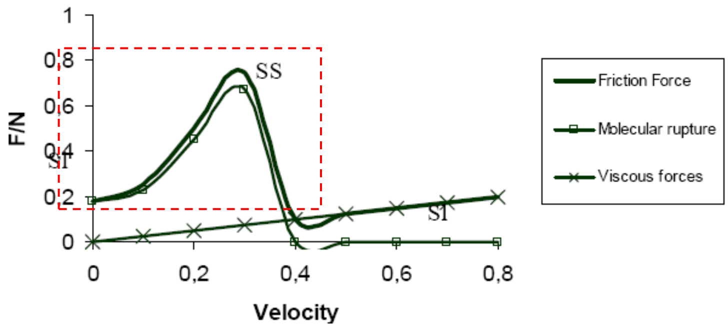

Figure 5 - Velocity dependent on frictional forces [37]

Note: Figure 5 only shows positive velocities, but looking at the outlined section and mirroring this would show some similarity to figure 4.

2.3.6 Validating Models

Validation is concerned with determining whether the simulation model is an accurate representation of the system under study [38]. Model validation involves comparing model predictions with real observations (data). In order to quantitatively assess the validity or predictive capabilities of the developed models, experimental observations need to be collected from targeted tests conducted in a well-controlled environment [39]. The confidence in model validation is closely related to the amount and quality of experimental observations, therefore the more validation data available the more accurate is the uncertainty quantification in the experiments and the more confidence in the model validation results.

The process of comparing model outputs with real outputs visually is similar to trace driven system validation as demonstrated in [40], where real-world data is input into a model, and the outputs of the model and real system are compared.

Validation can be split up for internal and external validation [41], internal validation involves simulating the model with a wide range of normal data sets. External validation involves simulating subsections of the models, for example using machine experiments (i.e. a square wave) to validate an actuators transient response.

Internal validation can be investigated using a variety of techniques, for example Root Mean Square (RMS) calculated on the error of the actual and modelled output signal. The RMS error is a measure of the difference between the predicted model values and the values actually produced from system to be validated.

The Amplitude Ratio of signals can be analysed by comparing the models signal output with the actual systems output. For the exact same amplitudes the amplitude ratio = 1, for a greater model amplitude the amplitude ratio is >1, and for a smaller model amplitude the amplitude ratio is <1. The Phase Difference of signals can be analysed comparing the output phase of the model to the real systems, expressed in degrees giving zero for a matched model output or ±degrees for a leading or lagging model response.

External validation investigating modelled components transient characteristics compared to the real system can be done via monitoring the response to a step input and analysing the rise time, settling time, and overshoot. The Rise time is the time taken for the response to go from 10% to 90% of its final value. The Settling time is the time taken for the response to reach and remain within 5% of the steady state value, and the Overshoot is the amount in which a response exceeds the steady state value [42]. The characteristics of a response signal can be seen in figure 6.

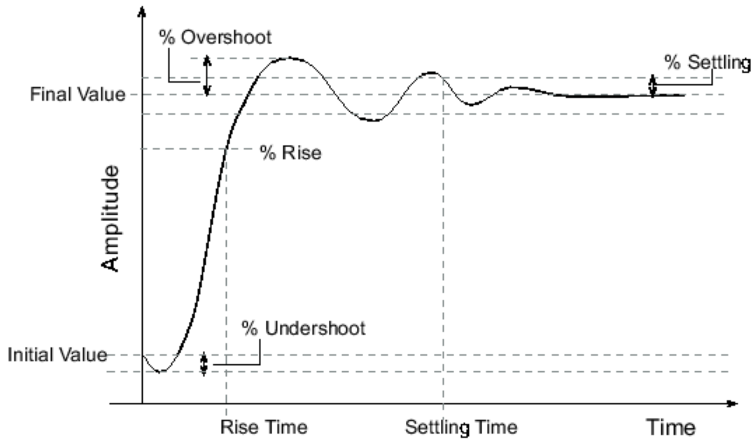

Figure 6 - Characteristics of a response signal

2.3.7 Fault Detection

A fault can be defined as a departure from an acceptable range of an observed variable or a calculated parameter associated with a process [43]. The underlying cause of this abnormality is called the root cause. With increased systems complexity it is becoming difficult for human operators to continuously diagnosis systems, manage system degradation, parameter drift, and component failures. This difficulty is compounded by production pressures, the amount of system variables, and incomplete or unreliable data. Fault Detection and Isolation (FDI) deals with timely detection, and diagnosis of abnormal system behaviour, once detected the human operator is able to take action accordingly.

Over the years different computer based diagnosis techniques have been tried and tested in a number of different domains. For the simpler and well understood systems, techniques such as decision trees, fault directories, and probability theory have been successfully applied [44, 45]. When applying these techniques with more complex systems, the accuracy of results reduces resulting in incomplete and inconsistent diagnosis. This is due to the fact that a high number of interactions could exist, therefore more complex techniques have been developed and used.

More complex techniques such as artificial intelligence has been used in the fault diagnosis area, but limitations such as incompleteness and inconsistencies in knowledge, knowledge extraction, and the dependency of the extracted knowledge exists [46]. To reduce these limitations fault diagnosis by the use of model-based techniques was considered. This involves capturing knowledge about the structure and behaviour of the system, and the key system interactions. Simulating the knowledge alongside the system can then be used to predict the system behaviour, and identify when a fault has occurred and diagnose it. This is done by the model generating the systems nominal behaviour, and any deviations identified.

Model based FDI techniques have been researched widely in the literature, examples being [47-51]. This involves creating a residual signal by comparing the systems actual output signal and the estimated one from a nominal system model. Once created this residual signal can be used as the indicator of abnormal system behaviour. An example of residual indication can be seen in figure 7.

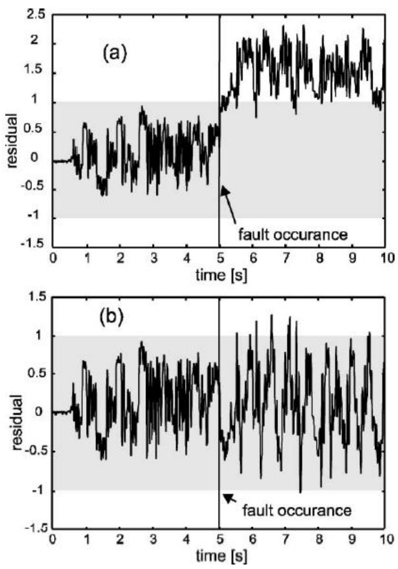

Figure 7 - (a) Detection of a sensor offset fault, (b) detection of a sensor gain fault. [50]

As the fault occurs in figure 7 the residual in a) appears out of its threshold, in b) there is a frequency change but the majority of the residual stays within the threshold. There is a threshold present due to system modelling uncertainties and noise. Figure 7 identifies that faults can be detected but not simply by residuals appearing out of tolerance.

FDI focuses on the use of fundamental knowledge to achieve efficient and effective diagnosis. Models of the correctly functioning system which can generate the expected system behaviour are used to express the fundamental knowledge. Comparing the systems behaviour with the models behaviour can give the ability to derive possible faults, but the fault detection accuracy depends greatly on the existence of a good system model [52].

Other FDI techniques exist such as knowledge based methods [53] which don't involve an analytical model but are data-driven and knowledge based techniques able to estimate the system dynamics. Signal processing techniques in the time or frequency domain can also be applied to detect faults some examples of these are spectrogram and scalogram [54], and wavelet decomposition [55].

Productivity loss and abnormal system behaviours can be avoided by early detection and diagnosis of faults, figure 8 shows the components of a general fault diagnosis framework and indicates the three types of failures that could occur in a controlled process:

- Parameter changes: such as temperature or coefficient modifications.
- Structural changes: equipment failure i.e. stuck valves, leaks, or controller board failures.
- Faults in sensors or actuator: these would degrade the controller's performance and therefore the systems performance.

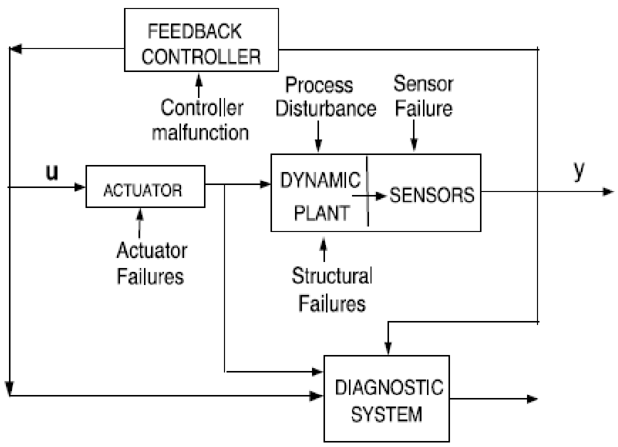

Figure 8 - A general diagnostic framework [56]

2.4 Literature Review: Soft Systems

Although this thesis is primarily developing a model of a hard system, this section will be a short review of the soft systems theory to enable a holistic understanding of the system.

Soft Systems Methodology (SSM) aims to engage with people and their environments, to try to resolve issues using a variety of tools or methods which encourage learning usually of the cyclic nature [57]. Therefore SSM has been described as a learning cycle methodology, with the learning leading to new situations, and broadening the researchers views of the system; giving the possibility of positively affecting the problem situation [58]. The original SSM cyclic learning system was introduced by [2] and has been updated and criticised throughout the years, but [1] argues that the methodology is still frequently used and its application for this project will be demonstrated within this chapter.

[2] seven stage SSM can be outlined as follows:

1. Entering the problem situation.
2. Expressing the problem situation.
3. Formulating root definitions of relevant systems.
4. Building Conceptual Models of Human Activity Systems.
5. Comparing the models with the real world.
6. Defining changes that are desirable and feasible.
7. Taking action to improve the real world situation.

Reviewing Checkland's [2] *model entering the problem situation*; involves exploring and defining the real world problem. Following the definition of the problem situation a rich picture can be used to investigate into the systems structure, processes, climate, people, issues expressed by people, and conflicts. *Formulating root definitions of relevant systems*, and *building conceptual models of Human Activity Systems*; arguably can be the most challenging part as it involves understanding the different perspectives which can drawn out of the rich picture. Finding out what the system is occurs in *Formulating root definitions of relevant systems, Building Conceptual Models of Human Activity Systems requires further use of soft systems analysis.* The remaining three steps: *Comparing the models with the real world*, *Defining changes that are desirable and feasible*, and *taking action to improve the real world situation,* involve comparing the model with the real world to identify improvements, re-check analysis, to make sure the problem situation is fully understood. The final parts may be an iterative process where the whole cycle could restart again.

This thesis is primarily concentrating on a hard system, but to appreciate and understand the soft systems elements surrounding the hard system for a holistic approach, just two of the seven steps SSM will be investigated in depth for this research. These are *Formulating root definitions of relevant systems (stage 3), Building Conceptual Models of Human Activity Systems* (stage 4) to explore these stages the mnemonic CATWOE will be used. Introduced by [59] CATWOE is a useful method to understand different perspectives of the people involved in the system, and gain a holistic soft systems view of the problem to enable conceptual models to be developed. [60] provides a useful summary of the elements of the CATWOE definition in Table 1:

Customers:	The affectee(s) of the transformation process.
Actors:	The agents and their specific core-competences participating in the transformation process.
Transformation Process:	Transformation process of 'needs for' into 'needs met'.
World View:	The 'Weltanschanuung' making the transformation process meaningful from the different affectees perspectives.
Owner:	The decision maker with power and responsibility for the overall performance of the system.
Environmental Constraints:	The internal and external environmental constraints influencing the transformation process.

Table 1 - CATWOE (Gibbons, 2011)

Arguably the most important factors of CATWOE are the Transformation process 'T' and World View (or in German Weltanschauuugen) 'W' [52]. These are the most important factors as CATWOE is used to define rigorous and comprehensive root definitions, and at the heart of the root definition is the process which is surrounded by its world view to make it meaningful [52]. A review of the literature indicated that the preferred definition of 'T' is "*need for X -- T → need met*" [61]. A number of measurements have been identified to monitor and control purposeful 'T' [44]:

- Effectiveness: e.g. T is correct/wrong activity to be doing
- Efficacy: e.g. the way T is done does/does not work
- Efficiency: e.g. T is/is not done with minimum resources (for example time)

To gain a rich understanding of the root definitions the 'W' in this context means "*what view of the world makes the situation meaningful*" [44]. Taking an holistic approach it is useful to recognise every 'A' or groups of 'A' will have a different viewpoint, therefore each one is meaningful and should be taken into consideration. [45] argues that the 'W' can be further broken down to improve its meaning, into:

W1: represents the W in CATWOE - given-as-taken set of assumptions

W2: represent the version of the problem statement making W1 relevant

W3: represents our beliefs and assumptions about reality and makes us understand social situations

The Customer 'C' is defined as the beneficiary or victim of the system's activity [59], i.e. as further illustrated in [46] discussion, 'C' refers to any affectees of 'T'. Those who would do 'T' are defined as 'A' Actors, the 'A' can help identify knowledge or competence needed in order to accomplish the modelled 'T' [62].

To enable a clear understanding of the 'O' and 'E' the systems map in figure 9 is presented as developed by [60]:

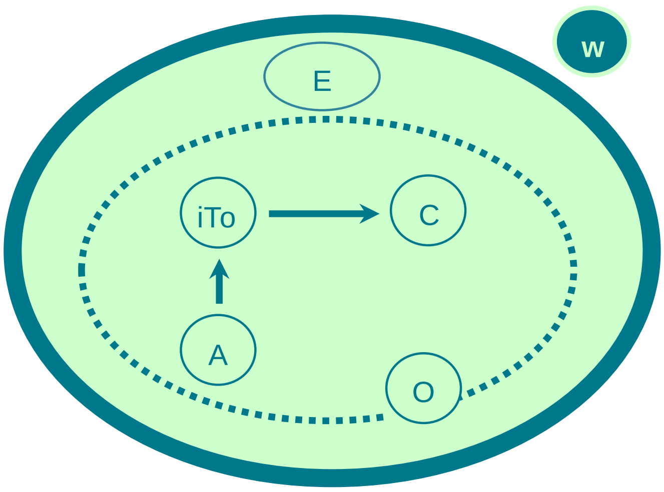

Figure 9 - CATWOE systems map [60]

As can be seen in figure 9, the 'O', Owner is on the next level to 'C', 'A', and 'T' (iTo, refers to the Input-output process of the transformation). 'E' is on the next level above 'O' encapsulating the environment of the system, customers, actors, and owner.

2.5 Conclusion

This literature review has covered the hard and soft systems aspects of this thesis. Modelling of the LF60 will be accomplished by creating an analytical model of the system, and the human interactions will be captured by utilising a Value Improvement Model (VIM) which builds on the use of CATWOE.

The following chapter outlines the research methodology used within this thesis.

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Chapter 3: Research Methodology

3.1 Introduction

This chapter outlines a relevant sample of research methodologies available from the literature, then justifies why a mixed (quantitative and qualitative) approach is required to develop solutions to the research questions. In summary a quantitative approach will be used for the development of an analytical model, alongside a qualitative approach using action research, encompassing ethnography for the human understanding parts of the research. Developing a robust research framework, the combination of qualitative and quantitative research gives a triangulated approach [1] and has been used by other researchers based in industry (see [2] for example).

3.2 Research Paradigm

[3] argues a research paradigm is an interpretative framework which is guided by a set of beliefs and feelings about the world and how it should be understood and studied. Four research paradigms are presented by [3], positivism, post-positivism, critical theory, and constructivism arguing research methodologies are guided by the type of research paradigm taken. [4] describes positivism as a view that any phenomena experienced can be described by knowledge, and the purpose of science is to stick to what we can observe and measure. Therefore a positivist would not hold any knowledge beyond that. A post-positivist is a view that we need context and that context free experimental design is insufficient [5]. The theory that knowledge is not value free and bias should be articulated relates to critical theory [6], and constructivism can be described as individuals constructing their own reality so there are multiple interpretations [7]. The research within this thesis will be using a mixture of positivism and post-positivism due to the experimental nature of the research combined with the human interaction understanding.

Table 2 presents a useful summary of research paradigms, the corresponding research approaches, and a sample of their research methods adapted from [8].

Research paradigms	Research approach	Research methods
Positivism	Quantitative	Surveys **Analytical Modelling** Cross-Sectional Design
post-positivism	Qualitative	Interviews **Ethnographical;** Grounded Theory Case study **Action research**

Table 2 - Selection of the research paradigm and methodology, adapted from [8]

With an understanding of the applicable research paradigms for this project, the following section reviews a relevant sample of research approaches and methods.

3.3 Research Approach and Methods

According to Bryman & Bell, the research approach can either be of a qualitative or quantitative data type. Quantitative research refers to research of social phenomena via mathematical, statistical, or computational techniques [9]. In contrast, qualitative research refers to achieving an in-depth understanding of human behaviour and the reasons that govern such behaviour [10].

[11] presents a useful sample of relevant research designs from the social scientist research literature which will be reviewed here also discussing their suitability to this research investigation.

3.3.1 Surveys

[12] argues, surveys aim to measure variables by asking people questions where the results are then examined to identify any relationships among the variables. The aim is to capture attitudes or patterns of past behaviour, and for this reason surveys are an exploratory means of capturing data, which can include biases due to the questions asked. A benefit of a survey analysis can include its cost-effectiveness. As this research project will be looking to create an analytical model using mathematical modelling implemented through working closely with the system users, a survey approach is not applicable. However, a survey could be used after the research has been completed to gain an understanding of the systems users experience of the new model.

3.3.2 Cross Sectional

Cross sectional research refers to a methodology which takes a look at one specific point in time at a large number of people (or organisations), to investigate economic characteristics [13]. This type of methodology is beneficial for economically describing attributes of large numbers of people (or organisations) but it lacks in explaining why the observed patterns are there [14]. Therefore this approach will not be used on this research project as the objective is not to gain an understanding at a single point in time, but to develop a new model to aid in fault detection and prediction.

3.3.3 Analytical Modelling

Analytical models are mathematical models that have a closed form solution, i.e. a mathematical analytic function can be used to described changes in a system [15]. Simulations and forecasting can be investigated by using time series analysis or regression analysis to make informed predictions [16]. Simulations can be effectively combined with these techniques to achieve models which copy the behaviour of a system, then the outputs are used in a comparative method i.e. model outputs vs. actual outputs, to check for any changes [17]. These changes usually referred to as residuals can be used to monitor for internal system changes therefore notifying of system changes which could indicate faults [18]. For this research investigation, analytical modelling is very applicable and will be used to develop a model of the system independent of human interaction.

3.3.4 Interviews

[19] defines interviews as a purposeful conversation in which one person asks prepared questions (the interviewer) and another answers them (the respondent). They are used to gain information on a particular topic or a particular area to be researched. The main drawback of this research methods can be the time needed to collect and analyse the responses, and due to the varied nature of response content analysis techniques could be needed to analyse them [20]. Advantages include freedom for respondent to answer how they wish [20]. For this research semi structured interviews will be used to enable an understanding of how best to implement the modelling work with the machine and its users.

3.3.5 Grounded Theory

[21] describes grounded theory as a general methodology for developing theory that is grounded in data systematically gathered and analysed. Grounded theory provides a systematic method involving several stages which is used to ‘ground’ the theory, or relate it to the reality of the phenomenon under consideration [22]. The main advantages of this research method is its attention to complexity, variability and context of social/psychological [21], one disadvantage can be said to be its positivistic roots, meaning not sufficiently acknowledging the role of the researcher and dependence of observations on theory and perspective [21]. Grounded theory is not applicable to this research project as the objective is not to develop an understanding of phenomenon under consideration.

3.3.6 Case Study

Exploratory research regarding phenomenon of interest can be described as case study research [13]. Advantages of this research method can be opportunities for innovation, it is a good method to study rare phenomena, and a good method to challenge theoretical assumptions [13]. Disadvantages include the method being hard to draw definite cause-effect conclusions, and possible biases in data collection and interpretation [23]. The case study approach is not totally applicable to this research project as the researcher will be embedded in the organisation. However, the outcomes of the research project could be written up as a case study for inclusion in any published work.

3.3.7 Ethnography

Ethnography literally means writing about foreigners [24]. This research method can be described as finding a way to uncover and explicate the ways in which people in particular work settings come to understand, account for, take action, and otherwise manage their day to day situation [25]. Advantages of this method include the ability to obtain first hand observations, disadvantages include the conclusions of what's been observed could be altered by the observers cultural bias or ignorance [26]. For this research project ethnography can be used to gain an understanding of the existing practices of the system users in the development of a new model taking into account their particular work settings.

3.3.8 Action Research

Action research involves a collaboration between the researcher and researched parties, forming a cycle of planning, observing, and reflecting [27]. The advantages of action research are the collaboration between the necessary parties, as participation of the researcher generally generates commitment and participation providing more complete information [28]. Disadvantages can include the researched parties change in habits due to an outsider participant taking part in the activities [28]. There is a good fit between the action research approach and the requirements of this research investigation which is to develop a new system of operation working closely with the existing system users.

3.3.9 Summary

A selection of research methods has been reviewed and arguments made that analytical modelling can be used for the creation of the LF60 simulation model alongside action research, ethnography, and semi structured interviewing which will see the author placed within the business monitoring the human interactions of the process for a holistic understanding of the system.

3.4 Research Design and Validity

The analytical modelling will be demonstrated in the first half of the thesis, where the modelling of the LF60 machine is accomplished by using the modelling/simulation packages Matlab and Simulink. The second part of the thesis shows the qualitative approaches used, where the researcher has been placed into the Rolls-Royce environment to observe the workings of the machine and its operators in order to gather data on the human interactions. Developing a robust research framework, validity and reliability are two important features for establishing and assessing the quality of research which must be understood [29]. For the quantitative research methods validity will be shown by model simulation to make sure the analytic model developed matches the operation of the actual LF60 machine, by visually and numerically comparing outputs. Validity and reliability for the qualitative approach will be based on gaining a good relationship with the observants to try to minimise deception [30].

3.5 Research Ethics

Ethics in research can be described as "the appropriateness of your behaviour in relation to the rights of those who become the subject of your work, or affected by it" [31]. Therefore it is important to consider a number of ethical issues which are discussed in [32]:

- **The subject firm:** what if the company you are researching are doing something illegal?
- **Confidentiality/anonymity:** what if the participant you are researching is doing something illegal?
- **Informed consent:** potential participants should be informed and agree to participate.
- **Dignity:** research should not ridicule or embarrass participants.
- **Publications:** must be honest and not be falsified to suit the researcher.

The factors defined by [32] applicable to this research are informed consent, dignity and publications. Therefore any participants of the research will be made fully aware of their involvement, with full respect given, and with any publications there approval given where necessary.

3.6 Conclusion

Developing a robust research framework, this chapter has reviewed and discussed a relevant sample of the research paradigms, approaches, and methods. Through this understanding and discussion, the most appropriate ones to be used for this research are presented. Due to the nature of the research being experimental and with the involvement of humans a mixed research paradigm will be used, using both positivism (quantitative) and anti-positivism (qualitative) paradigms, giving a holistic approach to the research. This can be seen in table 3, alongside the corresponding thesis chapter where the methodologies are demonstrated.

Research Paradigms	**Research Approach**	**Research Methods**	**Thesis Chapter**
Positivism	Quantitative	Analytical Modelling	4-6
Post-positivism	Qualitative	Action Research Ethnographical Semi-Structured Interviews	7

Table 3 - Research Methodology for this Research

With a mixed research methodology now understood, the next chapter will develop the analytical model for the system under review as the first stage in developing a holistic understanding of the LF60 manufacturing process.

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Chapter 4: Modelling

4.1 Introduction

This chapter describes the dynamic modelling of the LF60 LFW system. A paper on this chapter has been published in the Fluid Power and Motion Control (FPMC'12) proceedings of the Bath/ASME Symposium [P1].

Initially the LF60 LFW production system purpose and description will be discussed, and then an overview of the welding process and the system axes will be given.

The LF60 is a linear friction welding system that is designed to weld Blisks in a production environment. The system uses a combination of high performance, high accuracy servo-hydraulics to produce oscillatory motion between the components which creates frictional heating, and a forging force sufficient to produce a high strength and geometrically precise bond.

The welding process can be divided into six phases: *contact* - initial advancement of actuators seating the blade onto the disc stub and applying a seating force, *ramp up* - blade oscillations start to occur, *conditioning* – maintaining the oscillations to enable frictional heat to build up, *burn-off* – material deforming plastically under compression, *ramp down* – blade decelerated to a static position, and *forging* – allowing the weld to complete under a constant pressure. Figure 10 outlines the process phases.

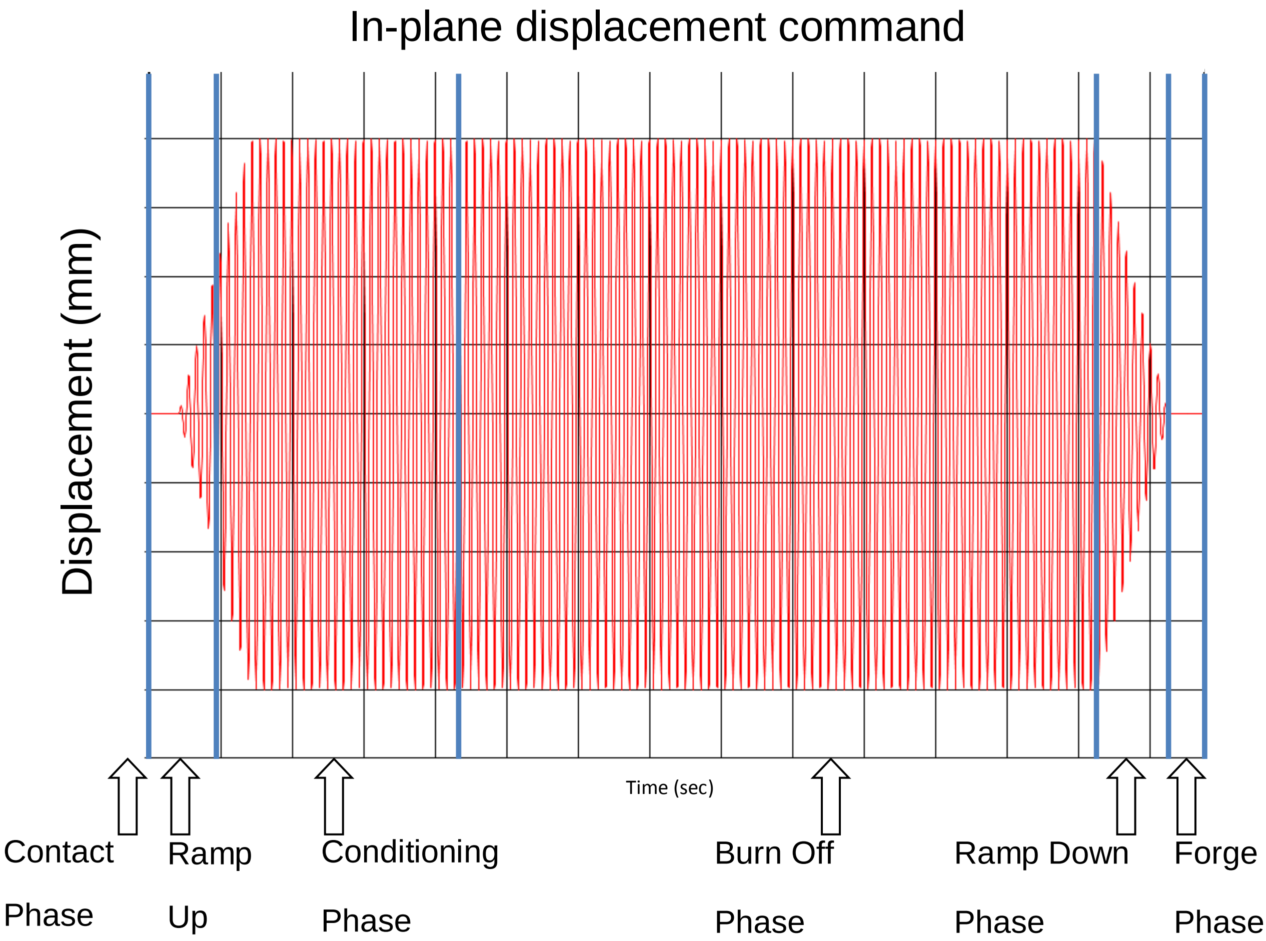

Figure 10 - LFW Process phases

Each machine axis is independently controlled using a combination of Proportional, Integral, Derivative (PID), or Amplitude, Phase (APC) control methods. The six axes are referred to as in-plane, Forge, Hade, Roll, Pitch and Yaw. The in-plane actuator is driven by a four stage valve controlled by PID and APC methods enabling tangential movement. Forging pressure is obtained by a combination of four independently PID controlled hydrostatic actuators. The six PID controlled hade actuators restrain the unwanted movement in other directions [1].

A picture of the LF60 in its production environment, and a CAD model outlining the inner cage axes can be seen in figure 11 and 12 respectively.

Figure 11 - LF60 in its production environment

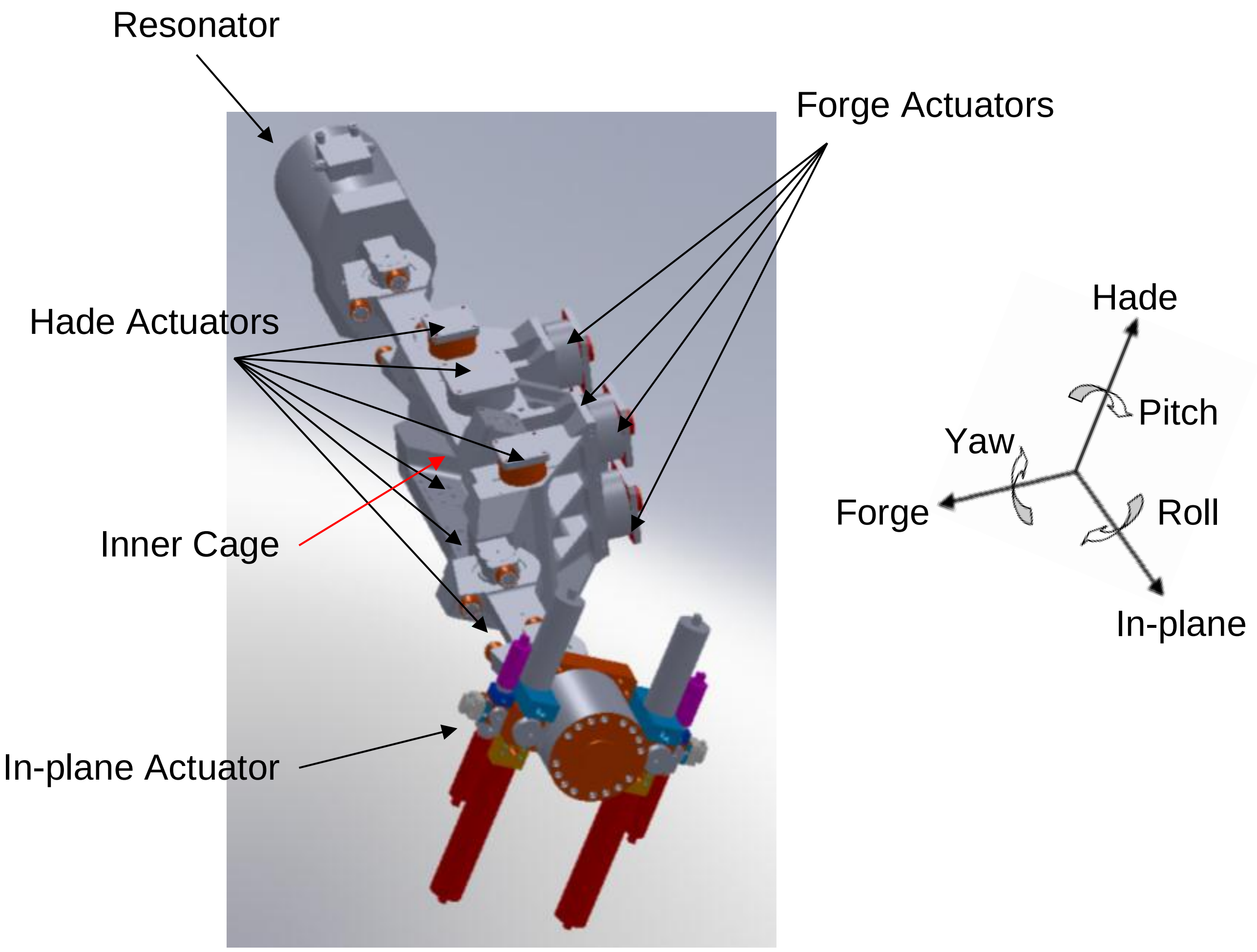

Figure 12 - Picture of the Inner cage with actuators attached and inner cage axes

4.1.1 LF60 Modelling Overview

The modelling of the LF60 will be done with the aim of using the modelled subsystems for fault diagnosis. The most frequently occurring and expensive faults occur with the complex in-plane system, therefore not all of the LF60's hydraulics and control system will be modelled. The modelled systems on the LF60 can be seen identified in figure 13; blue indicates systems to be fully modelled, red indicates partial modelling as appropriate for the in-plane system, and orange indicates the information is to be obtained from the LF60 machine post weld.

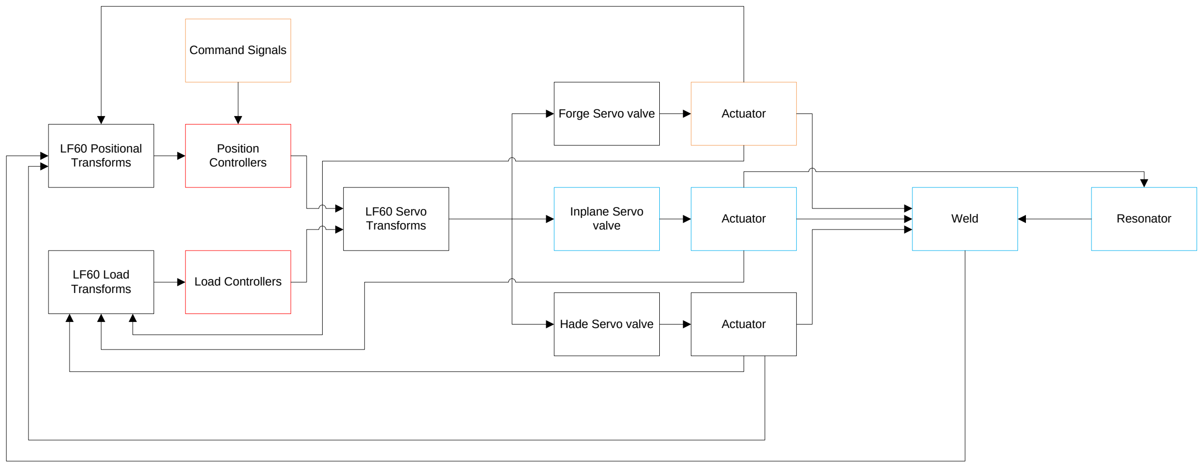

Figure 13 - LF60 Top Level system outline

For the purpose of this research only the in-plane actuation system, resonator and weld interface will be modelled.

For the modelling in this research the in-plane system is of key importance due to the number of faults which have occurred in the past on the system. The modelling needs to be accurate for the faults to be detected before they occur. Figure 14 outlines the top level of in-plane systems to be modelled.

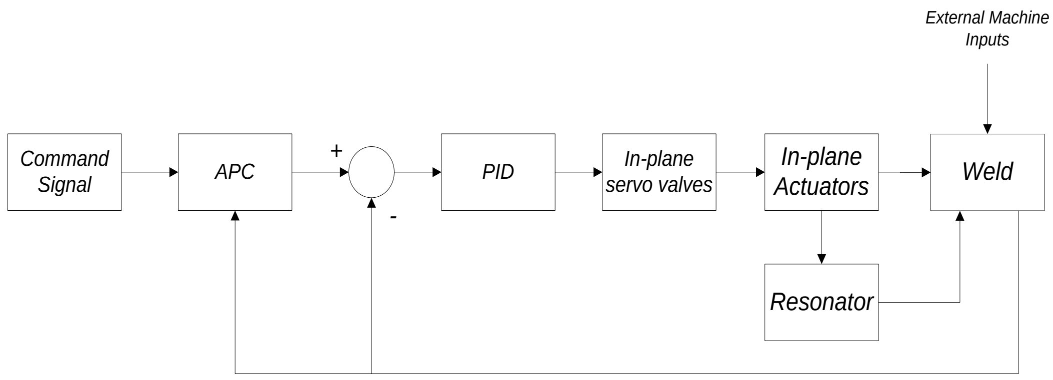

Figure 14 - Top Level of in-plane system

The modelling needs to be effective in detecting and/or predicting faults, therefore the modelling needs to be accurate enough to track small changes in the machines signal outputs when compared to the modelling outputs.

Section 4.2 outlines the modelling of the LF60 in-plane system, including modelling of the controller, servo valves, actuators, welding forces, the resonator, and other important forces, then combines the subsystems to create the in-plane dynamic model.

4.2 Modelling of the LF60 In-plane System

4.2.1 Introduction

This section models the in-plane system. Subsection 4.2.2 outlines the input command signals and shows how the APC is modelled. Subsection 4.2.3 describes the modelling of the 4 stage servo valves. Subsection 4.2.4 models the actuator, and subsection 4.2.5 the welding dynamics and the resonator. Discussion of the modelling can be found in subsection 4.2.6.

4.2.2 Modelling of the Inputs and Controller

The LF60s in-plane system needs a fast and accurate position response for the production components to be of the required quality. For this reason two methods of controlling the in-plane system are used: PID and APC.

PID control is used for the inner loop, and the APC is used for the outer loop. The PID controller was modelled from the equation:

$$u(t) = K_P e(t) + K_i \int_0^t e(t)dt + K_d \frac{d}{dt} e(t) \tag{1}$$

The translation of equation (1) into a block diagram produces figure 15. Each of the PID components are discussed in chapter 2.3.4, and general PID operation is described in [2].

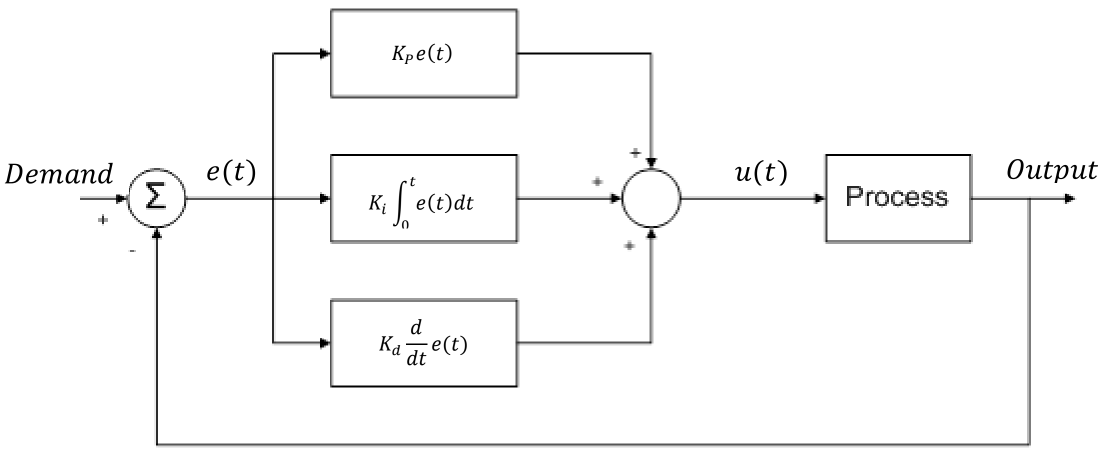

Figure 15 - PID block diagram

Modelling of the APC was done in Simulink, from the original patent developed by MTS Systems Corporation [3]. The APC modifies the control systems command signal using an inverse model of the PID-controlled in-plane actuator which is found via a Least Mean Squares (LMS) estimation method.

A detailed description of the APC algorithm can be found in [3]. For the reduction of any amplitude or phase errors the algorithm needs to determine the closed loop system's amplitude and phase so that suitable corrections can be made to the reference signal. This is done by an on-line estimated inverse model as shown in figure 16.

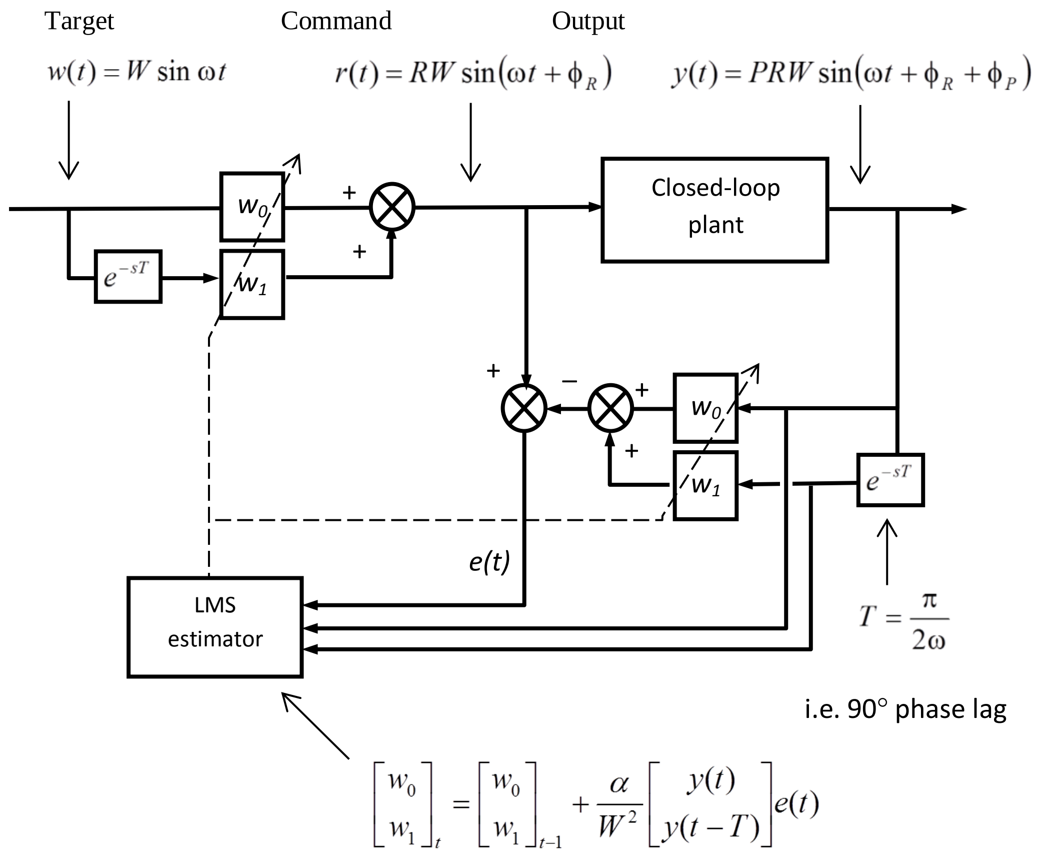

Figure 16 - APC schematic

The LMS Algorithm drives the error e(t) to zero by calculating weights ω_0 and ω_1. The error signal is the difference signal generated from a comparison of the sinusoidal component of the reference input signal and a phase and amplitude shifted signal derived from processing the feedback signal. The error is given by:

$$e(t) = r(t) - (\omega_0 y(t) + \omega_1 y(t-T)) \quad (2)$$

Or

$$e(t) = RW[\sin(\omega t + \varphi_r) - \omega_0 P sin(\omega t + \varphi_r + \varphi_p) + \omega_1 P cos(\omega t + \varphi_r + \varphi_p)] \quad (3)$$

Given a perfect inverse model to remove the error:

$$\omega_0 = \frac{1}{P}\cos\varphi_p \; and \; \omega_1 = \frac{1}{P}\sin\varphi_p \quad (4)$$

Applying equation 4 to the command signal gives:

$$R = \frac{1}{P} \quad and \quad \varphi_r = -\varphi_p \quad (5)$$

Therefore the plant output becomes the same as the original command (the target signal in figure 16)

The in-plane system model is validated in chapter 5, and the APC system will be included in the simulations. Therefore the APC will play a part in the models' overall accuracy.

4.2.3 Modelling of the 4th Stage Valves

The modelling of hydraulic systems has been widely covered in the literature [4-7]. Important modelling factors are outlined in [8], and include fluid compressibility, variable cylinder oil volumes, internal cylinder leakage, cylinder cross-port bleed, valve orifice pressure-flow characteristic, valve overlap, valve body pressure drop, manifold pressure drop and oil volume, valve spool dynamics, maximum valve opening, valve spool slew rate limit, friction, and geometric properties.

The in-plane actuator is driven by two 4 stage servo valves[2]. Each one has a pilot two stage valve rated at 1 GPM (gallon per minute); this drives the 3rd stage 40

[2] The valve rating in Litres per minute (LPM) are as follows: pilot stage 3.79 LPM, 3rd stage 151.42 LPM, 4th stage 1514.17 LPM.

GPM spool which in turn drives the 4th stage 400 GPM spool. Figure 17 shows a front view of the in-plane servo valves.

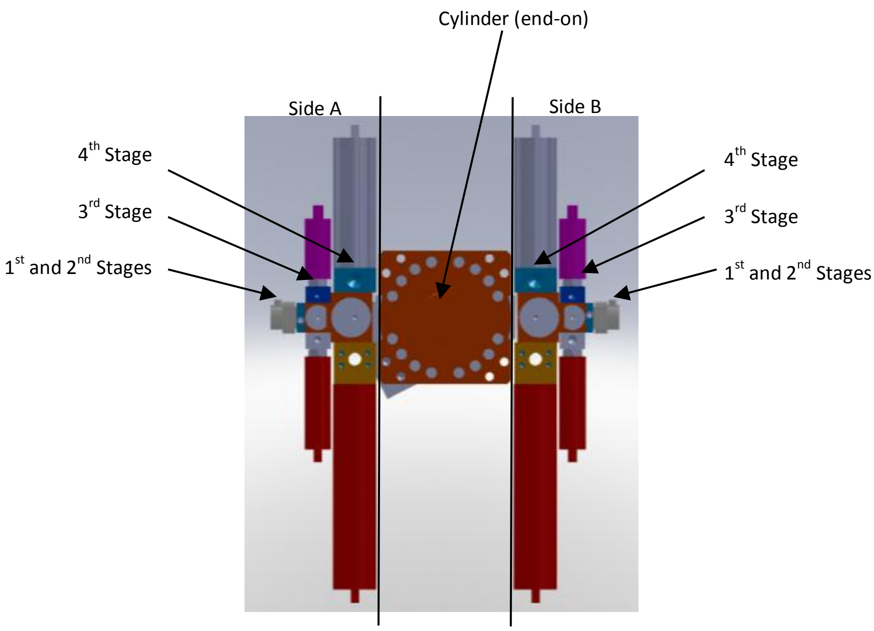

Figure 17 - LF60 4 stage in-plane Valves arrangement: front view

The in-plane system is driven from a command signal which initially starts in position control at zero displacement, ramps up to the required maximum sinusoidal amplitude which is held for the required time, ramped down and then held at zero load in load control as shown in figure 10. The 4 stage valve construction can be seen in figure 18.

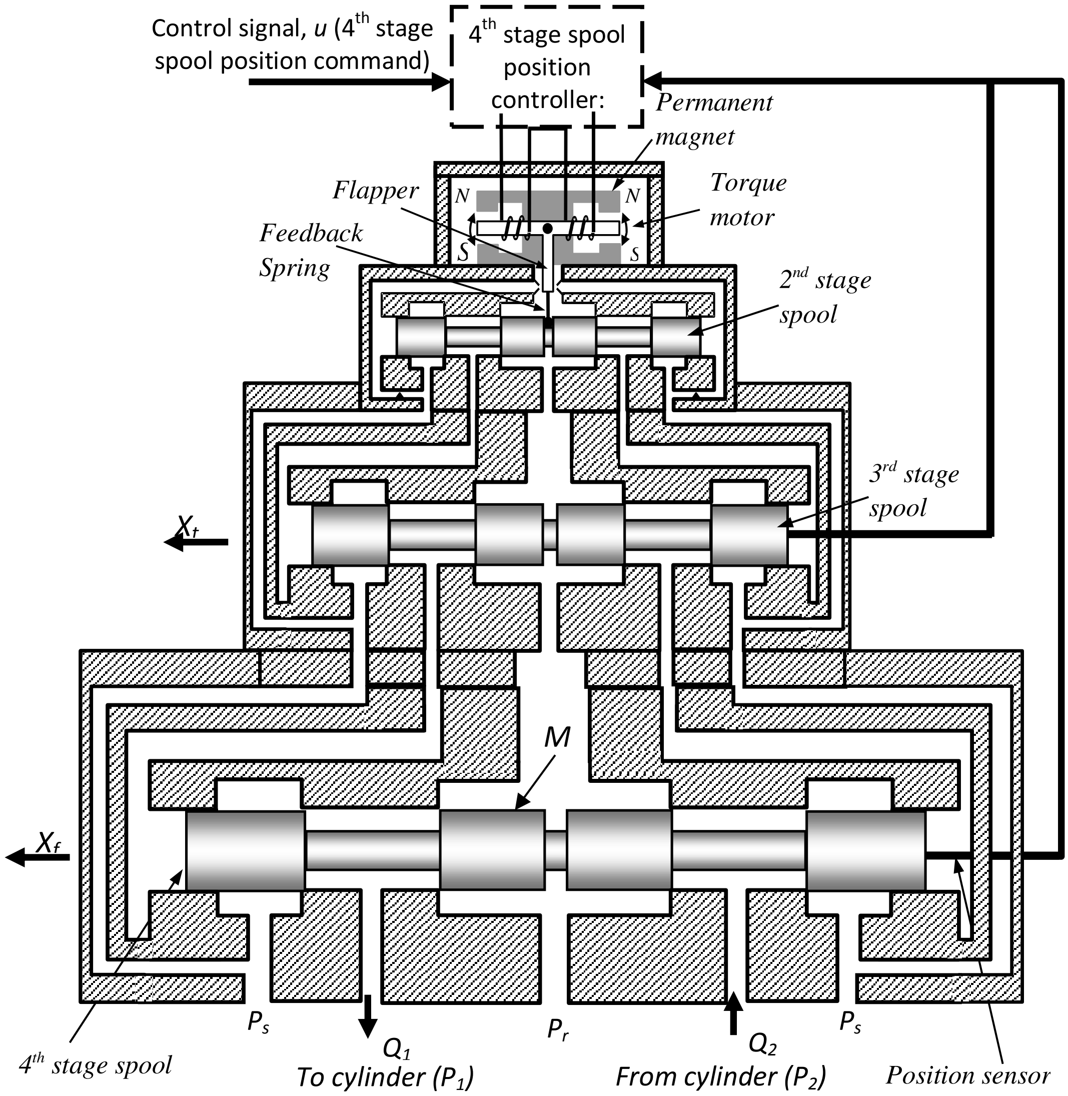

Figure 18 - Construction of one side of the LF60 4 stage valves

The 4 stage servo valve works by the 1st stage torque motor controlling flow via a nozzle-flapper arrangement to move the 2nd stage spool which is linked to the first stage by the feedback spring. The 3rd stage spool, with electronic position feedback, acts as a flow amplifier to the 4th stage, which also has electronic closed-loop control of the spool position.

The following equations model the 4 servo valve stages:

Two-stage valve model [9]

The spool dynamics are modelled as a delay and a second order transfer function:

$$\tilde{X}_s = \frac{e^{-sD}}{V(s)}\tilde{U} \tag{6}$$

Where,

$$V(s) = \left(\frac{s}{\omega_{ns}}\right)^2 + 2\delta_s\left(\frac{s}{\omega_n s}\right) + 1 \tag{7}$$

and where $\tilde{X}_s$ and $\tilde{U}$ is the spool movement and valve drive signal respectively, both normalised to ±1. δ_s represents the valve damping and ω_{ns} the natural frequency.

2nd stage valve orifice equations:

For positive $\tilde{X}_s$:

$$Q_{s1} = k_{vs}\tilde{X}_s\sqrt{P_s - P_1} \tag{8}$$

$$Q_{s2} = k_{vs}\tilde{X}_s\sqrt{P_{s2} - P_r} \tag{9}$$

For negative $\tilde{X}_s$:

$$Q_{s1} = k_{vs}\tilde{X}_s\sqrt{P_1 - P_s} \tag{10}$$

$$Q_{s2} = k_{vs}\tilde{X}_s\sqrt{P_r - P_2} \tag{11}$$

3rd stage model[3]

The 3rd stage spool motion is described by:

$$Q_{s1} = A_t\dot{X}_t + \frac{\dot{P}_{t1}}{k_{t1}} + (P_{t1} - P_{t2})c_t \tag{12}$$

$$Q_{s2} = A_t\dot{X}_t + \frac{\dot{P}_{t2}}{k_{t2}} + (P_{t1} - P_{t2})c_t \tag{13}$$

[3] Viscous friction has been ignored throughout the valve modelling stages

Where A_t is spool area, c_t is a leakage coefficient, and the fluid stiffness on each side of the spool is represented by:

$$k_{t1} = \frac{B}{V_{t1}} \; and \; k_{t2} = \frac{B}{V_{t2}} \tag{14}$$

And where B is the bulk modulus and V_{t1} and V_{t2} are fluid volumes which equal $v_{t1}$and v_{t2} when the spool is at mid position:

$$V_{t1} = v_{t1} + A_t X_t \; and \; V_{t2} = v_{t2} - A_t X_t \tag{15}$$

Spool force balance:

$$(P_{t1} - P_{t2})A_t = M_t \ddot{X}_t \tag{16}$$

Normalisation of spool movement:

$$\tilde{X}_t = \frac{X_t}{S_t} \tag{17}$$

Where s_t is half the stroke of the spool (i.e. the maximum value of X_t).

3rd stage valve orifice equations:

For positive $\tilde{X}_t$:

$$Q_{t1} = k_{vt} \tilde{X}_t \sqrt{P_s - P_{t1}} \tag{18}$$

$$Q_{t2} = k_{vt} \tilde{X}_t \sqrt{P_{t2} - P_r} \tag{19}$$

For negative $\tilde{X}_t$:

$$Q_{t1} = k_{vt} \tilde{X}_t \sqrt{P_{t1} - P_r} \tag{20}$$

$$Q_{t2} = k_{vt} \tilde{X}_t \sqrt{P_s - P_{t2}} \tag{21}$$

Where k_{vt} is the 3rd stage valve flow constant.

4th stage

4th stage spool motion:

$$Q_{t1} = A_f \dot{X}_f + \frac{\dot{P}_{f1}}{k_{f1}} + (P_{f1} - P_{f2})c_f \tag{22}$$

$$Q_{t2} = A_f \dot{X}_f + \frac{\dot{P}_{f2}}{k_{f2}} + (P_{f1} - P_{f2})c_f \tag{23}$$

c_f is a leakage coefficient, and the fluid stiffness on each side of the spool is represented by:

$$k_{f1} = \frac{B}{V_{f1}} \; and \; k_{f2} = \frac{B}{V_{f2}} \tag{24}$$

$V_{f1}$and V_{f2} are fluid volumes:

$$V_{f1} = v_{f1} + A_f X_f \;\; and \; V_{f2} = v_{f2} - A_f X_f \tag{25}$$

Spool force balance:

$$(P_{f1} - P_{f2})A_f = M_f \ddot{X}_f \tag{26}$$

Normalisation of spool movement:

$$\tilde{X}_f = \frac{X_f}{s_f} \tag{27}$$

Where s_f is half the stroke of the spool.

4th stage valve orifice equations:

For positive $\tilde{X}_t$:

$$Q_1 = k_{vf}\tilde{X}_f\sqrt{P_s - P_1} \tag{28}$$

$$Q_2 = k_{vf}\tilde{X}_f\sqrt{P_2 - P_r} \tag{29}$$

For negative $\tilde{X}_t$:

$$Q_1 = k_{vf}\tilde{X}_f\sqrt{P_1 - P_r} \tag{30}$$

$$Q_2 = k_{vf}\tilde{X}_f\sqrt{P_s - P_2} \tag{31}$$

Where k_{vf} is the 4th stage valve flow constant, and P_s is the main system pressure, as the modelling assumes accurate accumulator sizing and therefore very small system pressure drop during welding. The servo valve simulation and validation can be found in chapter 5.

4.2.4 Modelling of the Actuator

The dynamic characteristics of the hydraulic actuator are modelled in this section. The hydraulic actuator is a double ended equal area actuator as shown in figure 19. The model includes fluid compressibility, internal cylinder leakage, cylinder cross-port bleed, and coulomb friction. The actuator is modelled driving a mass M, with the welding load considered as an external force F.

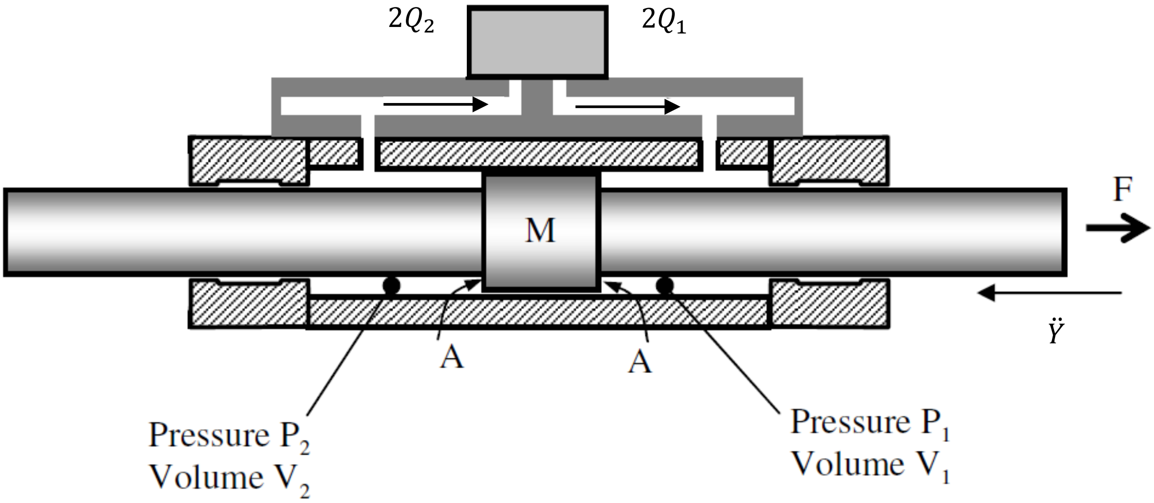

Figure 19 - Double ending actuator

Piston force balance:

$$(P_1 - P_2)A - F = M\ddot{Y} \tag{32}$$

where M is the total mass of piston, inner cage, and the tooling.

Cylinder flow equations:

$$2Q_1 = A\dot{Y} + \frac{\dot{P_1}}{k_1} + (P_1 - P_2)c + c_1\sqrt{P_1 - P_2} \tag{33}$$

$$2Q_2 = A\dot{Y} + \frac{\dot{P_2}}{k_2} + (P_1 - P_2)c + c_1\sqrt{P_1 - P_2} \tag{34}$$

Where the fluid stiffness on each side of the cylinder is represented by:

$$k_1 = \frac{B}{V_1}\ and, k_2 = \frac{B}{V_2} \tag{35 \& 36}$$

The validation of the servo valve and actuator models can be found in chapter 5.

4.2.5 Modelling of the Weld Dynamics and Resonator

4.2.5.1 Weld Force Modelling

Analytical and numerical models of the linear friction welding process studying the impact and contact dynamics have been investigated mainly by [10-13], describing the process, its variables, and validation of the models using software packages such as Forge2007. Analytic and numerical contact modelling of LFW aims to improve understanding of the physics and mechanics involved in objects which are moving and touching. Friction between the objects is the main factor involved in the process, and this can be described as static friction or dynamic friction [14]. Research from [15] showed that the instantaneous friction coefficient measured varied approximately linearly with blade velocity within certain boundaries, producing the empirical relationship as seen in Figure 20. Each of the graph segments are split into 0.2 second time intervals over the in-plane weld cycle.

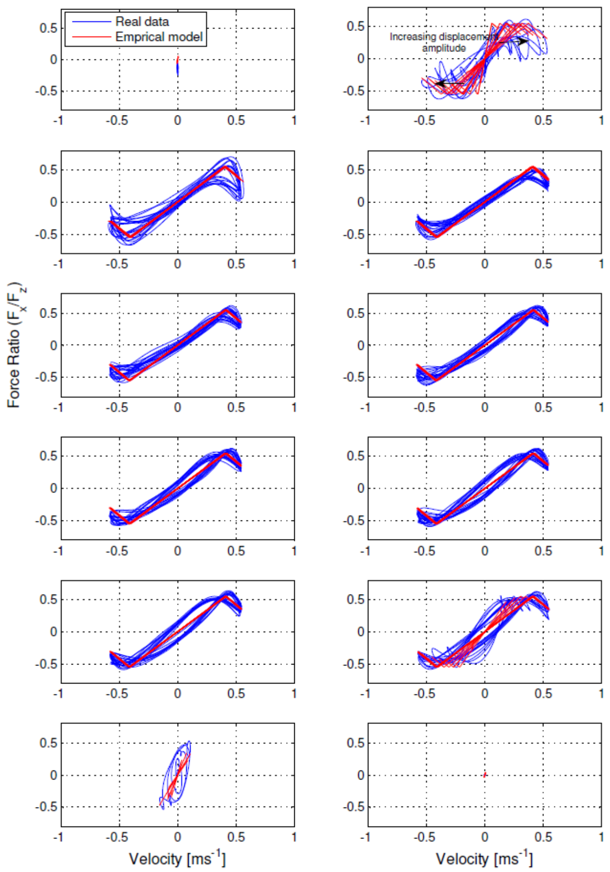

Figure 20 - Empirical relationship of the Friction coefficient velocity during the weld cycle

The empirical relationship determines the in-plane force at the weld given the in-plane velocity, maximum amplitude, and the total forging force. This is done by using a linear relationship as described in equation (37) and shown in figure 20.

$$F_{WELD} = F_Z f(A(t), v(t)) \tag{37}$$

Where F_{WELD} is the in-plane force at the weld, F_z is the forge force, $A(t)$ is the oscillation amplitude, and $v(t)$ is the oscillation velocity. The empirical function can be found in Appendix 1.

4.2.5.2 Resonator Model

The resonator is made up of three pistons, the main resonator piston, and two smaller ones forming piston accumulators on each side of the resonator. A diagram can be seen in figure 21.

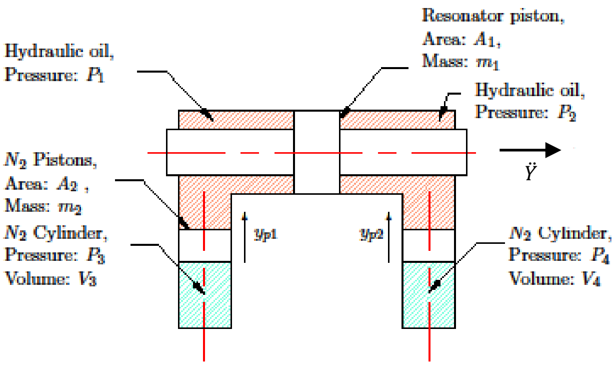

Figure 21 - Simplified Resonator diagram [15]

The resonator enables the in-plane actuator load requirement to be reduced by acting as a hydraulic spring to assist the acceleration of the inner cage at the operating frequency. Assuming that the main piston of the resonator is rigidly fixed to the inner cage, the resulting flow into the hydraulic oil volume on the left side of the piston is given by:

$$Q_{in} = -\frac{dx}{dt}A_1 + k(P_1 - P_2) \tag{38}$$

Where, k is a leakage coefficient accounting for the flow past the piston due to clearances. The flow out of this volume, determined by the movement of the left side resonator piston, where leakage is assumed zero (due to the need to keep the nitrogen and oil separate), is:

$$Q_{out} = -\frac{dy_{p1}}{dt}A_{p2} \tag{39}$$

To account for the hydraulic oil stiffness, the pressure in the oil volume (P_1) on the left side of the piston is related to the net sum of flows by the following expression:

$$\frac{dP_1}{dt} = \frac{B}{V}(Q_{in} - Q_{out}) \tag{40}$$

Where B is the oil bulk modulus and V is the initial volume of oil. The motion of the nitrogen pistons is given by Newton's second law as:

$$m_2\frac{dy_{P1}}{dt^2} = A_2(P_3 - P_1) \tag{41}$$

And the compression of the nitrogen gas is assumed to be a polytropic process governed by the expression:

$$P_3 = P_0\left(\frac{V_3}{V_3 + A_2 y_{P1}}\right)^n \tag{42}$$

Where n is the polytropic index and V_3 is the original volume of the nitrogen cylinder. Similar equations were developed for the right side of the resonator. The force applied to the in-plane system can then be found from the pressure differential across the resonator piston:

$$F_{RESONATOR} = A_1(P_1 - P_2) \tag{43}$$

This is a simplified model therefore is doesn't include friction between either the main resonator piston or the smaller nitrogen pistons against their bores.

4.2.5.3 Inertia and Friction Force

The rods connecting the inner cage to the in-plane actuator and resonator are assumed to be rigid and have been modelled as a mass M along with that of the inner cage and actuator and resonator piston masses.

The net friction force is approximated by.

$$F_{FRICTION} = \; F_C \tanh(\dot{y}) \tag{44}$$

Where F_C is a friction constant. The tanh function is used as an approximate estimation for friction as demonstrated in [16].

4.2.5.4 Summary

The weld and resonator forces modelled in sections 4.2.5.1, 4.2.5.2, and 4.2.5.3, combine to make the overall in-plane actuator force giving:

$$F = F_{WELD} + F_{RESONATOR} + F_{FRICTION} \tag{45}$$

The Simulink diagram representing this relationship can be seen in figure 22.

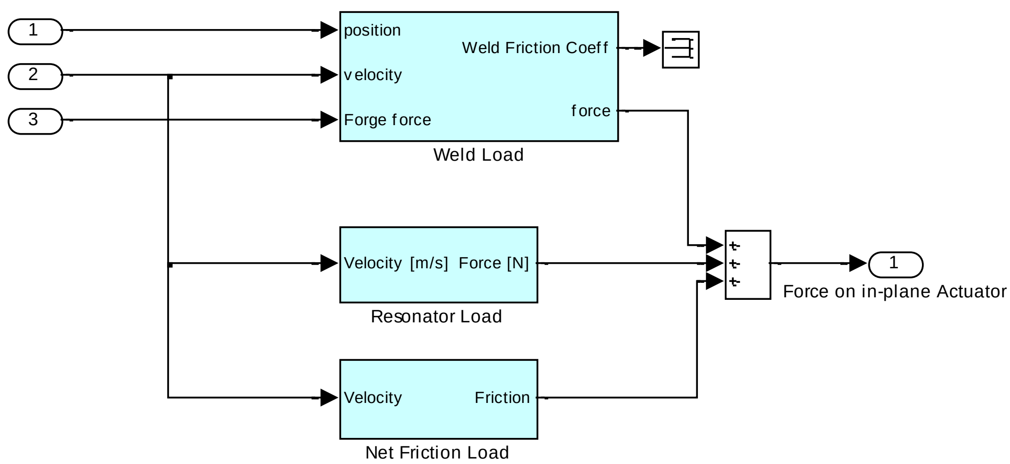

Figure 22 - Weld dynamics and forces Simulink model

4.3 Discussion

Chapter 4 has modelled the in-plane system including the controller, multiple stage valves, actuator, and the welding dynamics. The modelling has been combined to produce the in-plane system model which is simulated and validated in chapter 5.

The Simulink model diagram is shown in figure 23, showing the multiple modelled systems combined to create the in-plane system.

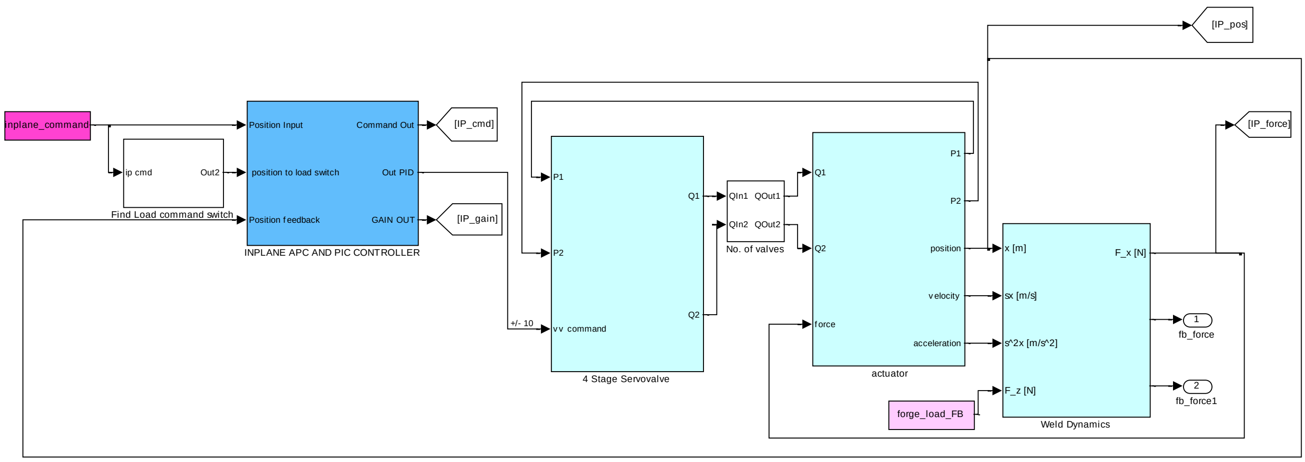

Figure 23 - Overview of in-plane System in Simulink

This chapter has contributed to answering the initial research question:

R1: *Can an analytical model be developed to accurately represent a complex physical electro-hydraulic system?*

The LF60 in-plane model has been developed, representing the complex physical electro-hydraulic machine axis. Chapter 5 determines its overall accuracy and suitability for use in detecting and predicting faults.

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Chapter 5: Validation

5.1 Introduction

This chapter focuses on the in-plane system validation verifying how accurate the modelling is compared to the actual LF60 system through a comparison of selected signal outputs using a variety of statistical measures. Some of these results have been published in the Fluid Power and Motion Control (FPMC'12) proceedings of the Bath/ASME Symposium [P1].

The model is validated by investigating the accuracy to a wide range of data sets under normal operation (internal validation), and specific machine test experiments (external validation). Internal model validation is a sensitivity analysis using a variety of data, and external validation is made using experiments to check the model validity. Similar techniques have been used to validate complex thermal models as in [1].

The internal model validation will be investigated using a number of techniques: Root Mean Square (RMS) error, Amplitude Ratio (AR), and Phase Difference (PD). The RMS value is a statistical measure of the magnitude of a varying signal. AR is the amplitude of the output sine wave divided by the input sine wave. The PD is the difference in phase of the model and the actual signal output [2]. Each analysis will be completed over the oscillating time period. This will enable the detection of any abnormal behaviour in the modelling and therefore quantify the model accuracy in relation to the actual system.

Section 5.2 outlines the model validation, describing the different data sets used, introducing the validation analysis method, results, concluding with a summary of the section. Section 5.3 describes a sub model which can be used for fault prediction, validates the model, and then summarises the validation findings. Section 5.4 concludes the chapter.

Table 4 and 5 identifies the parameters and their corresponding units used in the models simulation.

Symbol	Units	Value	Parameter Description
Controller parameters			
-	-	3	APC controller gain
-	-	160	APC controller phase
K_p	-	0.21	Proportional gain for outer loop PID
K_i	-	0.0004	Integral gain for outer loop PID
K_d	-	4	Derivative gain for outer loop PID
-	-	0.0255	Proportional gain for forth stage PID
-	-	0	Integral gain for forth stage PID
-	-	0	Derivative gain for forth stage PID
Supply data			
P_s	Pa	200×10^5	Supply pressure
P_r	Pa	6×10^5	Return pressure
B	GPa	0.9	Hydraulic fluid bulk modulus
Third stage valve parameters (256.04A-01)			
-	l/min	150	Three stage valve rated flow
-	Hz	150	90 degree lag frequency
-	dB	-8	Amplitude ratio at 90 degree lag frequency
-	%	0	Stage 3 spool overlap
-	%	0	Valve hysteresis
-	ms	5.33	Time for 100% step at max slew rate
-	l/min	1000	Body saturation flow rate
Fourth stage parameters			
A_f	cm^2	7.5	Spool area
s_f	mm	6.5	Half stroke
-	l	0.026	Half volume of trapped fluid
M_f	Kg	2.15	Mass of the fourth stage spool
c_f	l/min/bar	0.01	Cross piston leakage
-	Bar	$(P_s + P_r) / 2$	Starting pressure
k_{vf}	l/min	1500	Rated valve flow
-	Bar	35	ΔP to achieve rated flow
-	kN	0	Max flow force per land 1 Δp (bar)
-	kN	0	Max flow force per land 1 Δp (bar)

Table 4 - Modelling Parameter Table

Symbol	Units	Value	Parameter Name
Actuator parameters			
A	cm^2	419.6	Working piston area
-	mm	7.6	Total working stroke
-	mm	2	Buffer length
-	-	1	Buffer force constant
-	cm^3	3000	Total cylinder and manifold oil volume
M	kg	103	Actuator piston mass
c	l/min	7	Cross piston leakage at 70bar ΔP
c_1	l/min	0	Cross port bleed at 70bar ΔP
-	N	0	Coulomb friction force
-	bar	150	Cylinder starting pressure
Resonator parameters			
A_1	m^2	57×10^{-3}	Resonator piston area
-	m	0.178	Nitrogen piston diameter
k	$(l/min)^2$	20	Cross piston leakage
m_1	kg	121	Resonator piston mass
m_2	kg	10	Nitrogen piston mass
V	cm^3	7500	Trapped volume of oil, in one half
V_3	cm^3	250	Trapped volume of nitrogen
n	-	1.8	Polytropic compression index

Table 5 - Modelling Parameter Table continued

Note: Symbols with a ‘-’ are present in the model but not explicit in this chapter.

5.2 Validation Methodology

This section outlines the internal model validation methodology, reviewing the selected data sets used to validate the model, and outlines the method of analysis for the model validation.

5.2.1 Simulation Data Sets

A number of different Blisk types are welded on the LF60, and a selection of welds from three of these Blisk types along with a selection of 'other welds' will be used to validate the model. The 'other welds' are a series of modified parameter weld cases which are referred to as Cut-up Approval (CAP) or specimen welds. These welds are used to verify welding performance and are therefore processed using a set of modified welding parameters[4]. There will be a total of 17 test data sets to execute the model as outlined in figure 24.

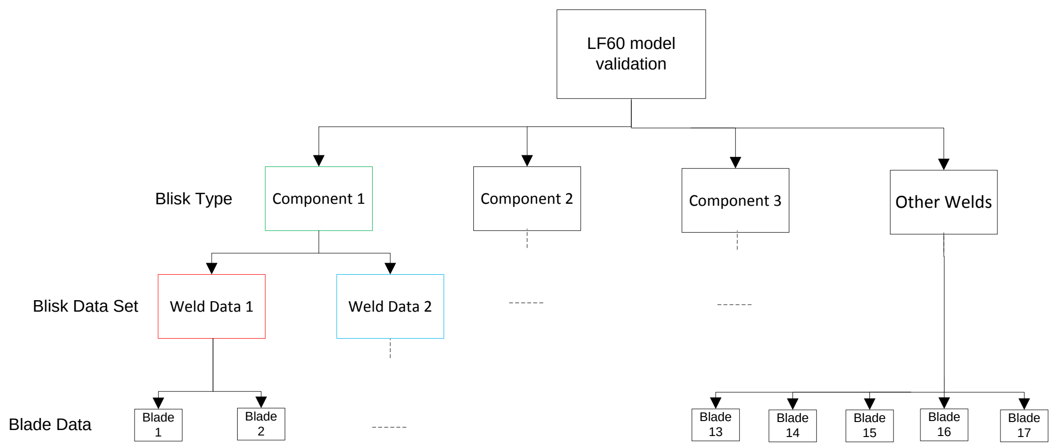


Figure 24 - Simulink in-plane Model Validation data set

Due to Rolls-Royce confidentially the exact parameters and their changes will not be defined, but the way in which the parameters are adjusted will be described.

Test 1 – 12: Are a range of 'nominal' welds for the various Blisk types.

[4] The precise details of the modified parameters are not discussed as they are Rolls-Royce Intellectual Property

Test 13: A ‘nominal’ weld with an extended in-plane command ramp down

Test 14: A weld with higher key process input variables

Test 15: A weld with lower key process input variables

Test 16: A ‘nominal’ weld with a slightly extended in-plane command ramp down

Test 17: A ‘plate’ weld with ‘nominal’ parameters

Prior to each of the validation tests, the model will be updated to represent the correct input variables for the welds.

The following section outlines how the model accuracy will be determined by using statistical validation methods.

5.2.2 Validation Analysis

For a quantifiable validation approach, a number of statistical measures will be applied to investigate the relationship between the model output and the actual system output when comparing the same signal. This section reviews the statistical measures and shows how they are applied to the validation procedure.

For each of the comparative (model vs. actual) signals, the results will be analysed using the following methods (over the oscillation period i.e. during the dynamic motion of the in-plane modelled system):

1. The Normalised Root Mean Square Error (NRMSE).

The NRMSE error is calculated on the error of the actual and modelled output signals. The actual Simulink function used is the *running RMS* value, which keeps a running total of the RMS error over the required time period. This value is then normalised by dividing the end value by the end value of the running RMS total of the actual signal output, an equation of the normalised RMS calculation can be seen in (1).

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}(x_{1,i} - x_{2,i})^2}{n}}}{\sqrt{\frac{\sum_{i=1}^{n}(x_{1,i})^2}{n}}} \tag{1}$$

The RMS error is a measure of the differences between the predicted model values and the values actually produced from the LF60. The normalised RMS value will be expressed as a percentage, with the lower values indicating better model comparison with the actual machine.

An example of the model simulation and steps taken to calculate the NRMSE can be found in Appendix 2.

2. Amplitude Ratio, Phase Difference and Frequency Check.

Amplitude Ratio is the ratio of the modelled signals amplitude compared to the actual signals amplitude, and the Phase Difference is the difference in phase between the signals, i.e. if one signal is lagging (or leading) the other (model – actual). The frequency of the actual and modelled signals will also be compared (i.e. model – actual). Matlab function files to calculate the above variables can also be found in Appendix 3.

5.2.3 Validation Results

This section reviews the validation for the in-plane system previously modelled in chapter 4. All modelled subsystems such as the controllers, valves, actuation, and dynamics are simulated for validation and then the individual signals compared against the actual system. A sample of outputs will be shown in this section and the remaining are shown in Appendix 4.

5.2.3.1 Validation Results: NRMSE

The main output signal of the in-plane system is the positional movement of the in-plane actuator. This needs to be accurate as it controls the inner cages tangential movement and thus where the welded blade is positioned onto the disk. Figure 25 displays the percentage errors of the model against the actual system for the in-plane displacement feedback signal across all the validation data sets. The worse of these data sets is the 11th in which the modelled signal has a 9% error when compared to the actual signal, the average error over all the data sets is 7%.

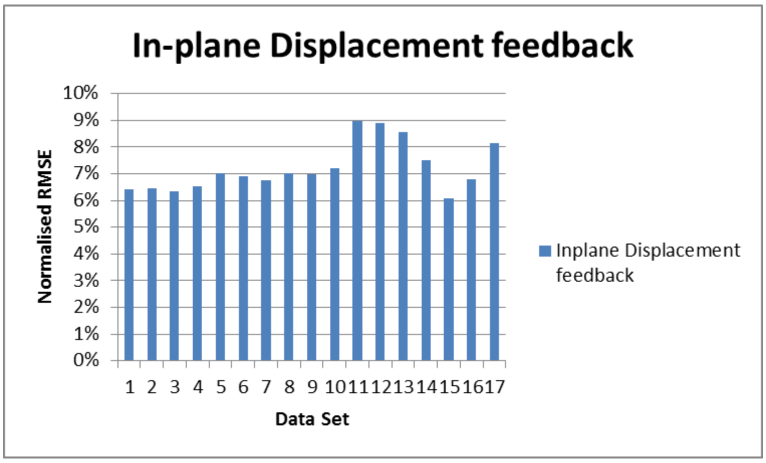


Figure 25 - In-plane Displacement NRMSE

Data set 11 represents one of the validation welds from the component 3 data set. These components are data sets 9 – 12, of which sets 11 and 12 are the worst. The explanation for this is a slight change in the machines performance over these two data sets, as the machines APC has been modified to account for changes in the valve performance over time.

The time series response for data set 11 is shown in figure 26, with zoomed in responses in figure 27. The responses show a slight time delay in the steady state response but a good modelled response during ramp up and ramp down.

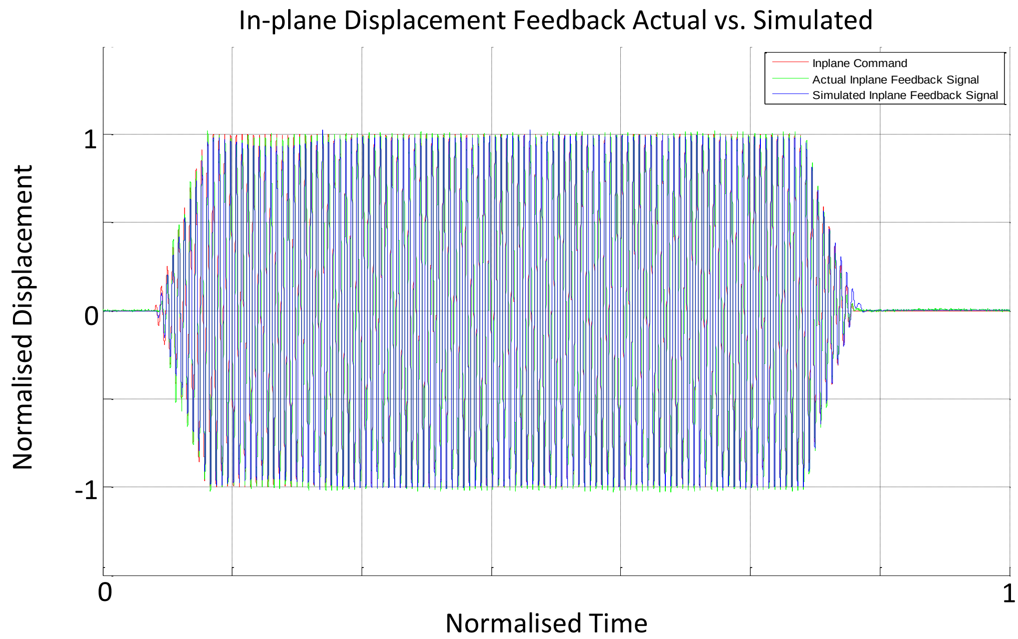


Figure 26 - In-plane Displacement Time Series

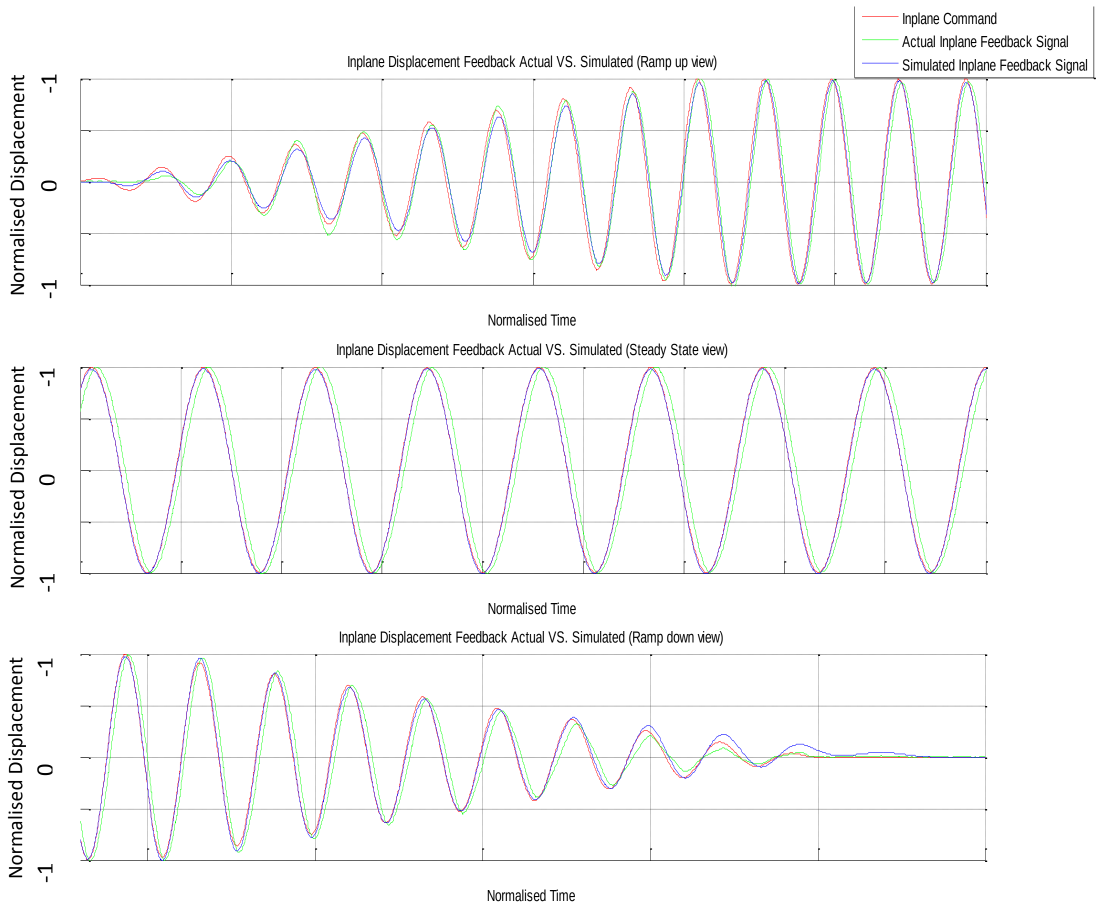


Figure 27 - In-plane Displacement Time Series zoomed in

The in-plane force generated by the in-plane actuation system is also an important aspect of the modelling. Due to un-modelled high order dynamics the NRMSE results are higher than the majority of modelled signals. NRMSE results are shown in figure 28, the average error is 41% and the maximum error is on the 14th data set at 49%.

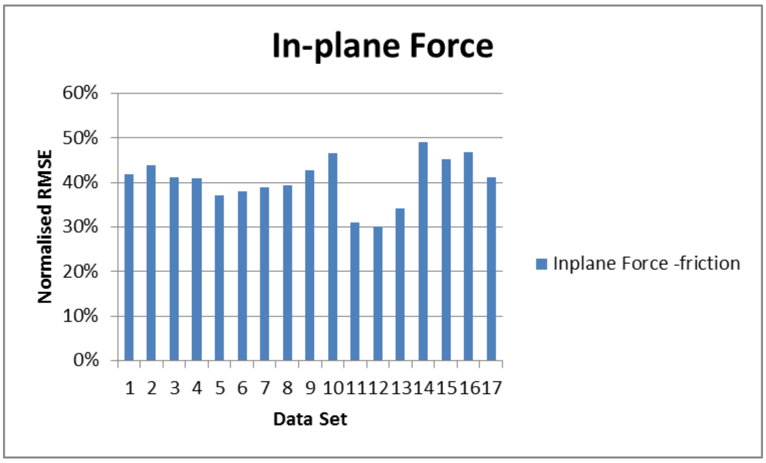


Figure 28 - In-plane Force NRMSE

The high frequency dynamic spikes of the actual signal are not present on the modelled signal, therefore the modelled signals accuracy is reduced, the time series data for the least accurate modelled signal vs. the actual signal can be seen on figure 29, and zoomed in responses are shown in figure 30.

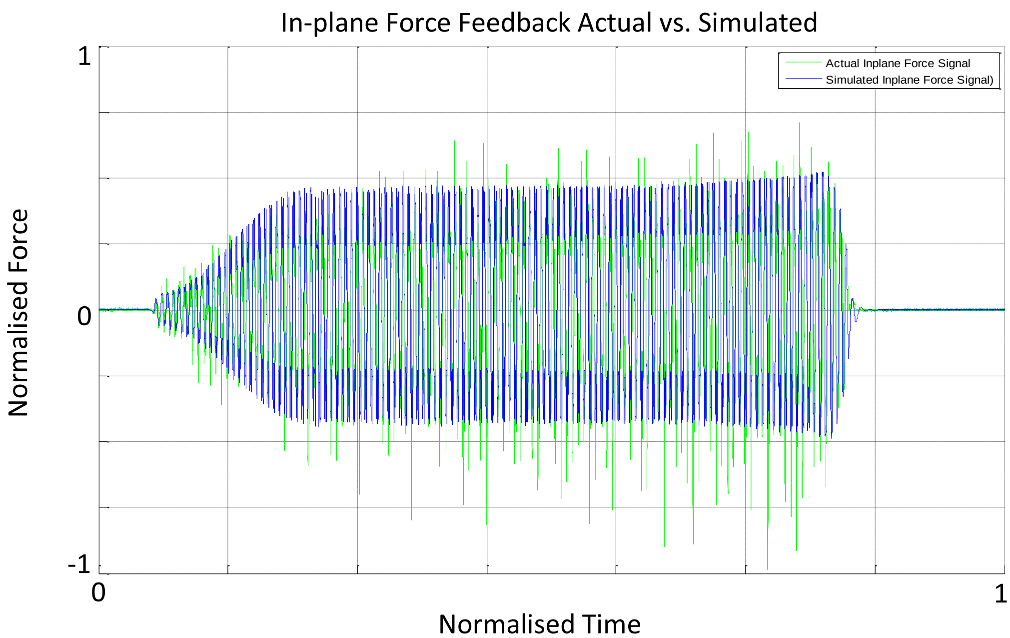


Figure 29 - In-plane Force Time Series

The frequency and phase response of the modelled signal is good, but the modelled signal does not capture the spikes seen throughout the actual signal.

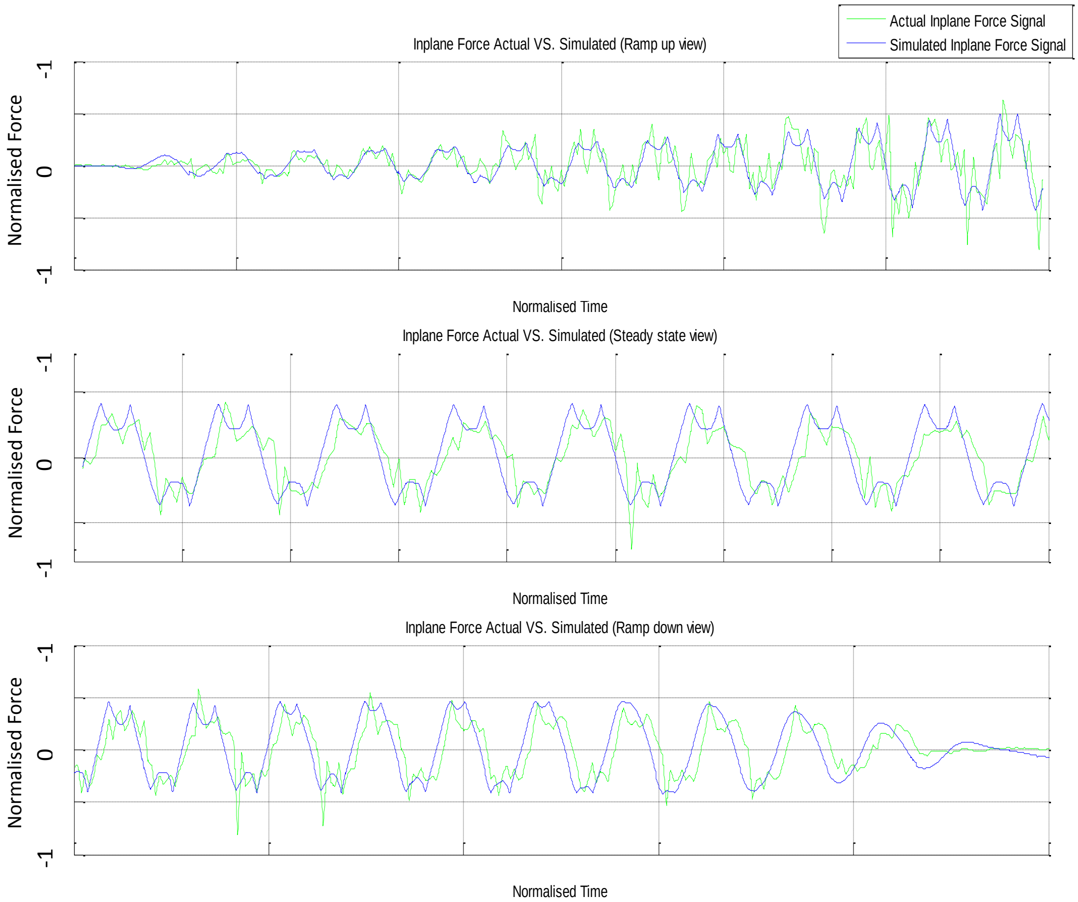


Figure 30 - In-plane Force Time Series zoomed in

The in-plane C1 and C2 pressures are also important measures as noticeable changes in these values could indicate issues related to the servo valve performance. For the in-plane C1 pressure the NRMSE values average at 21%, with data set 14 the worst at 24%. On review of figure 31 it is evident that the results are grouped into their components (i.e. data sets 1-4 have an average NRMSE of 22%, data sets 5-8 have an average NRMSE of 18%, and data sets 9-12 have an average NRMSE of 23%, the remaining data sets vary around these results.) The grouped results are related to the welding force area, the smallest area being data sets 5-8, and the highest welded area data sets 9-12. This concludes that an increased error on the modelled results is noticeable with an increased welding area on the component.

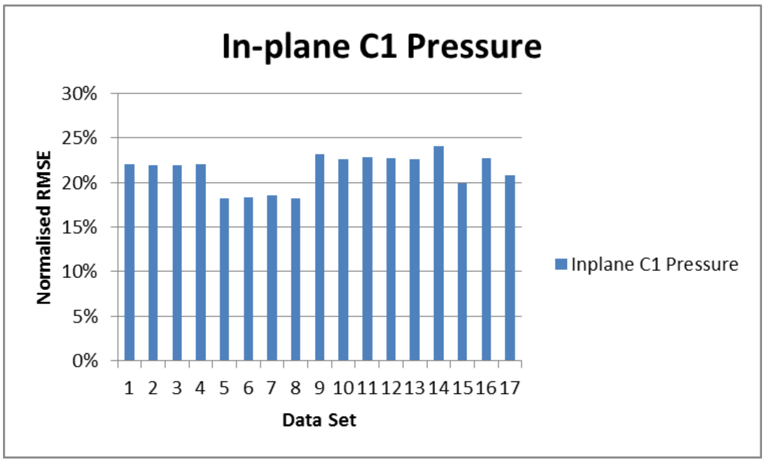


Figure 31 - In-plane C1 Actuator Pressure NRMSE

The time series data for set 14 which was the worse response can be seen in figure 32 and figure 33.

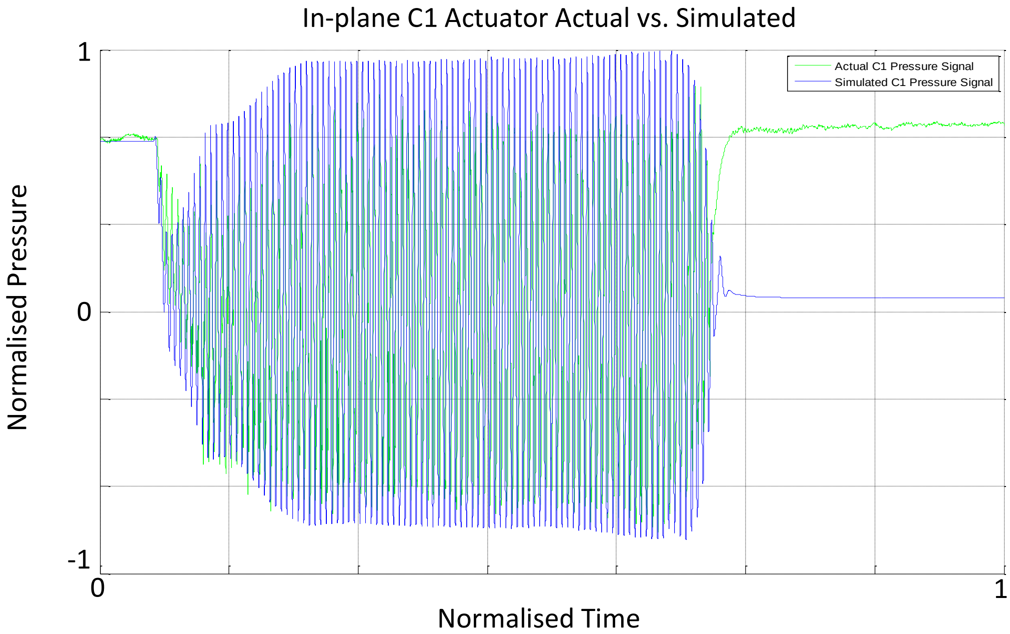


Figure 32 - In-plane C1 Actuator Pressure Time Series

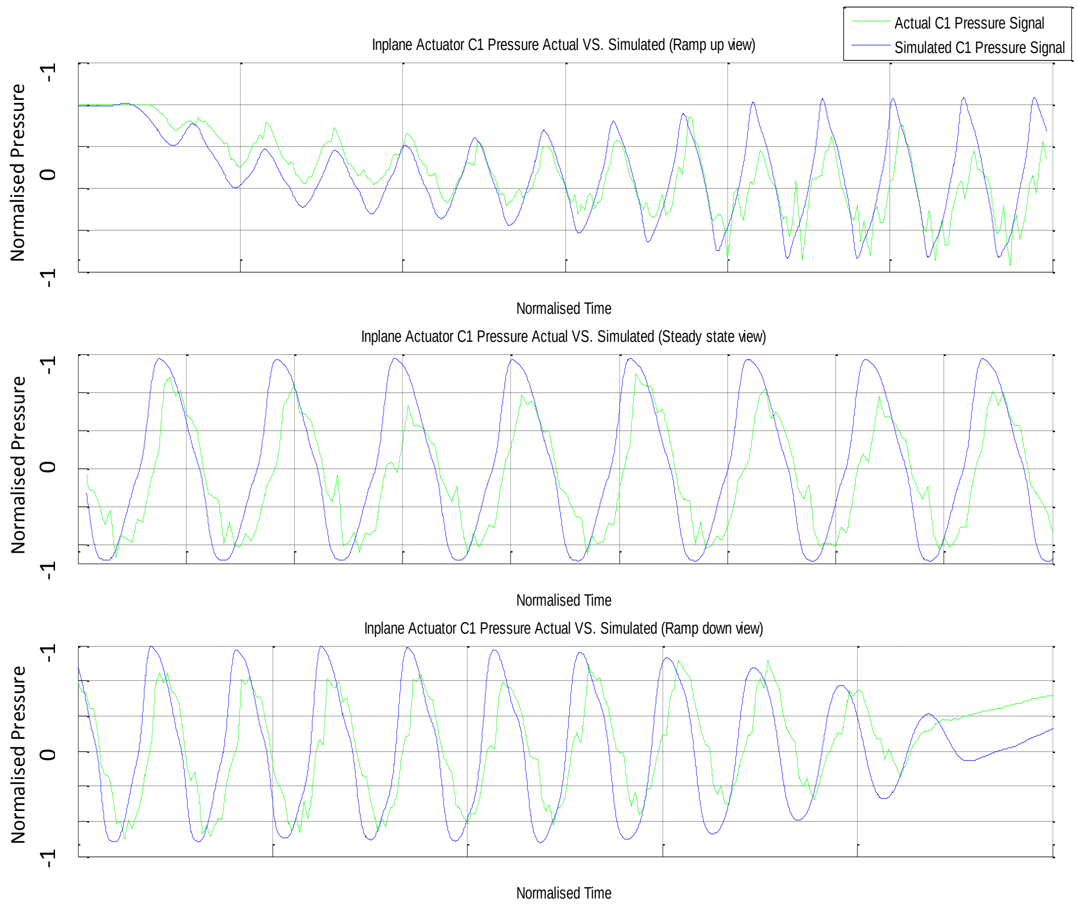


Figure 33 - In-plane C1 Actuator Pressure Time Series zoomed in

The NRMSE for the in-plane C2 pressure signal is shown in figure 34, averaging 22% with the worst data set being data set 14.

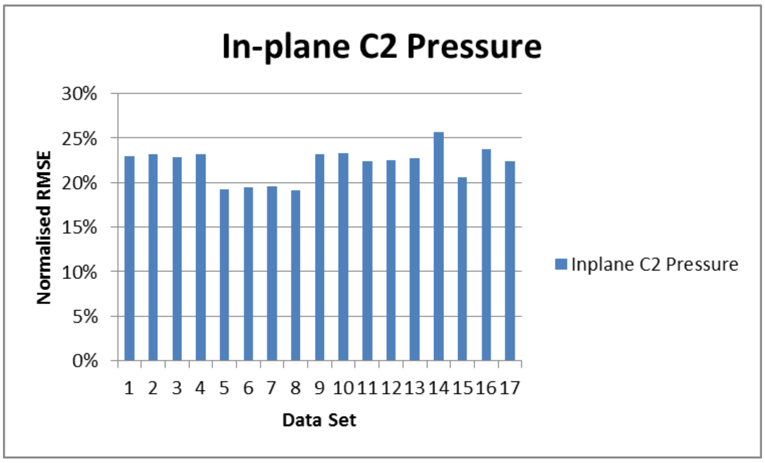


Figure 34 - In-plane C2 Actuator Pressure NRSE

Time series data is shown in figure 35 and figure 36.

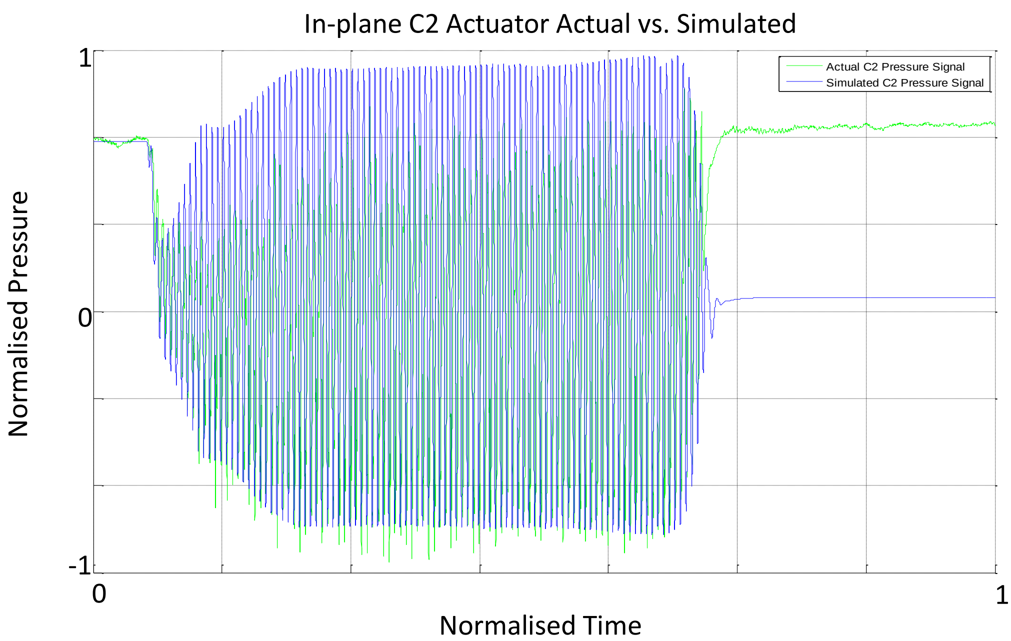


Figure 35 - In-plane C2 Actuator Pressure Time Series

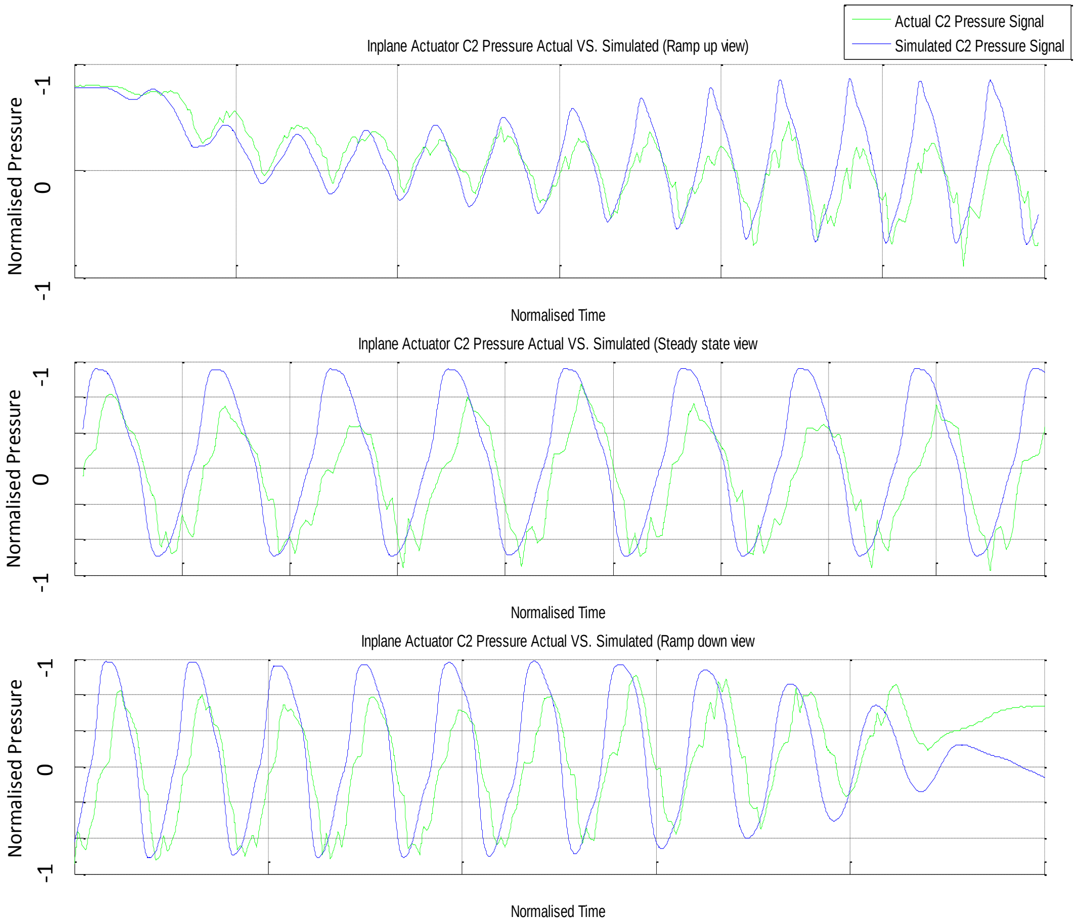


Figure 36 - In-plane C2 Actuator Pressure Time Series zoomed in

The NRMSE for the resonator load is shown in figure 37, averaging 13%. The maximum data set is the 15th at 17%.

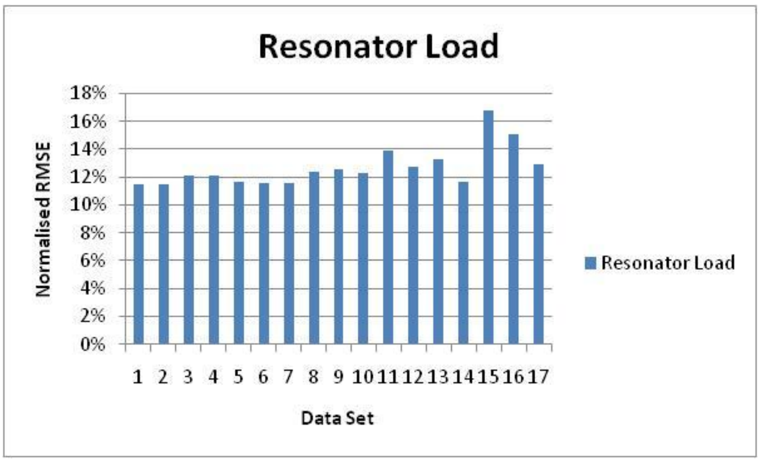


Figure 37 - Resonator Load NRMSE

Time series data can be seen in figure 38 and figure 39.

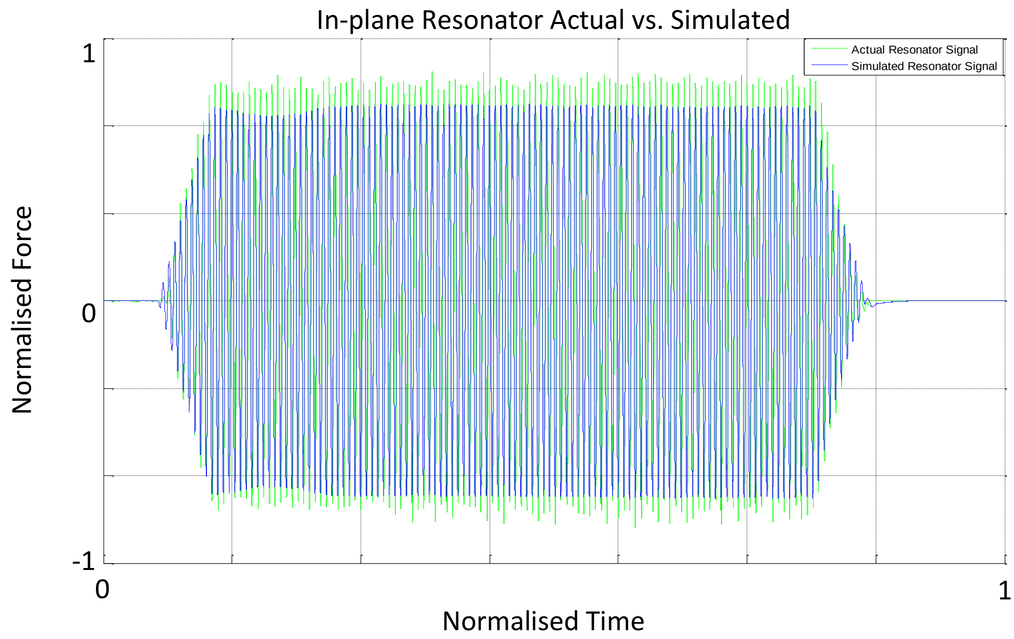


Figure 38 - In-plane Resonator Load Time Series

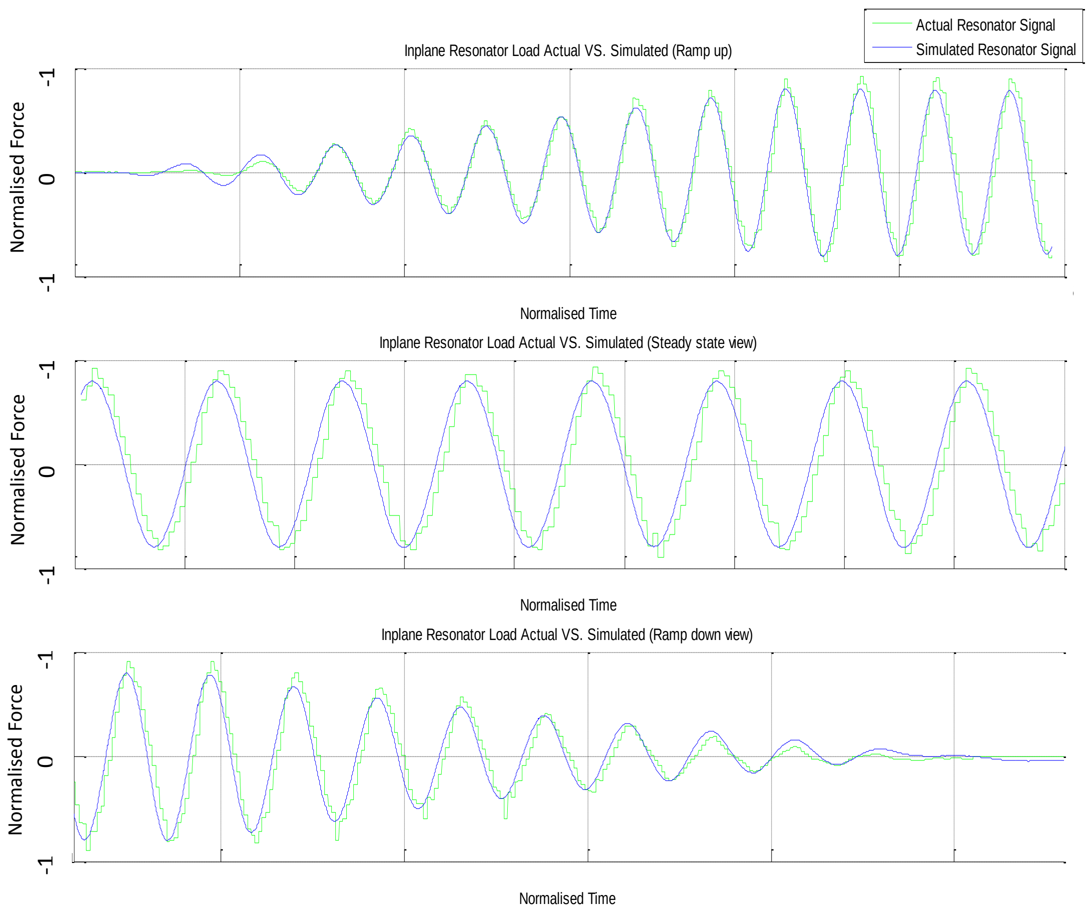


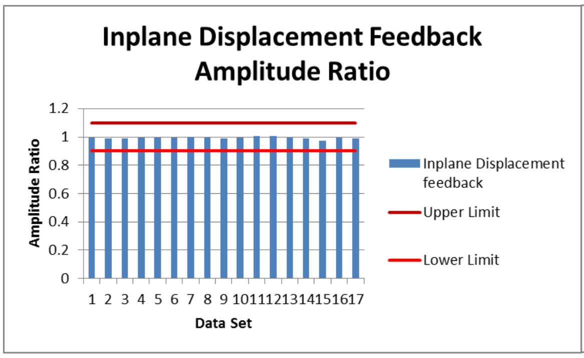
Figure 39 - In-plane Resonator Load Time Series zoomed in

The remaining validation results can be found in Appendix 4. The next section reviews the modelled signal amplitudes and phases in relation to the actual signals.

5.2.3.2 Validation Results: Amplitude Ratio, Phase Difference

The Amplitude Ratio and Phase Difference results are summarised in this section, the remaining amplitude ratio and phase difference results are shown in Appendix 5. These results are calculated during the oscillating part of the weld.

Limits have been set to gauge fault detection possibilities of the model. For the amplitude ratio a limit of ±10% has been set, and the phase difference limit has been set as ±10% of 360°. Figure 40 shows the in-plane displacement amplitude ratio and phase difference results, each of the data sets are within the specified limits, combined with the average NRMSE results of 7% this signifying the results for this modelled signal are good. There is a common phase difference throughout the results, this is due to the APC controller and a number of filters placed throughout the model.



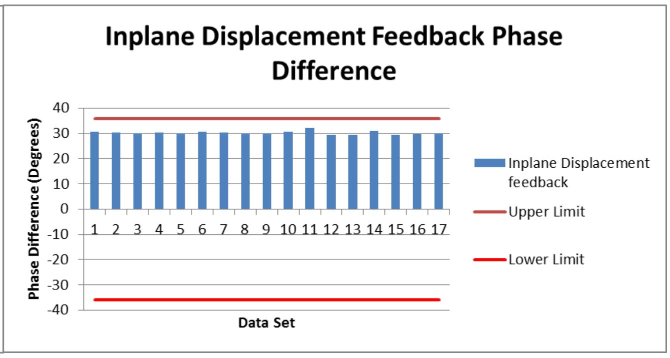


Figure 40 - In-plane Displacement AR and PD

Figure 41 shows the amplitude ratio and phase difference of the in-plane force modelled signal when compared to the actual signal. Even though spikes are present on the actual signal but not present in the modelling (therefore reducing the NRMSE accuracy) the AR and PD of the data sets for this signal are all within the specified limits.

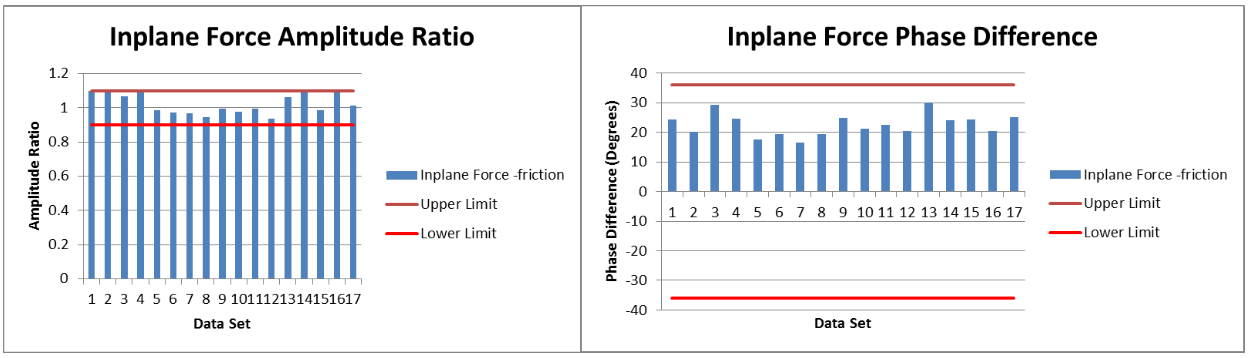


Figure 41 - In-plane Force AR and PD

Figure 42 and figure 43 show the in-plane C1 and C2 pressure AR and PD results respectively. These results are similar to the NRMSE results as they are also grouped into their components for the AR results. The majority of signal amplitude results are outside of their specified limits, and a few of the PD values are too. This would account for why the NRMSE were slightly high (around 22%).

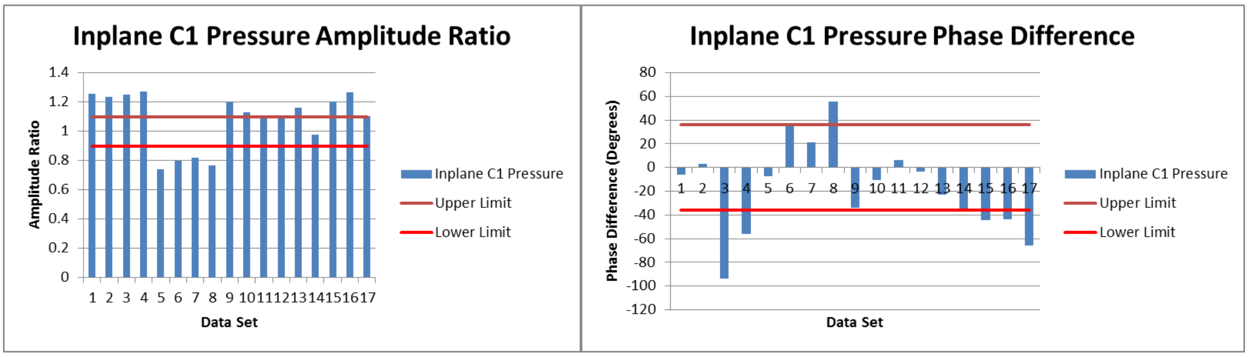


Figure 42 - In-plane Actuator C1 Pressure AR and PD

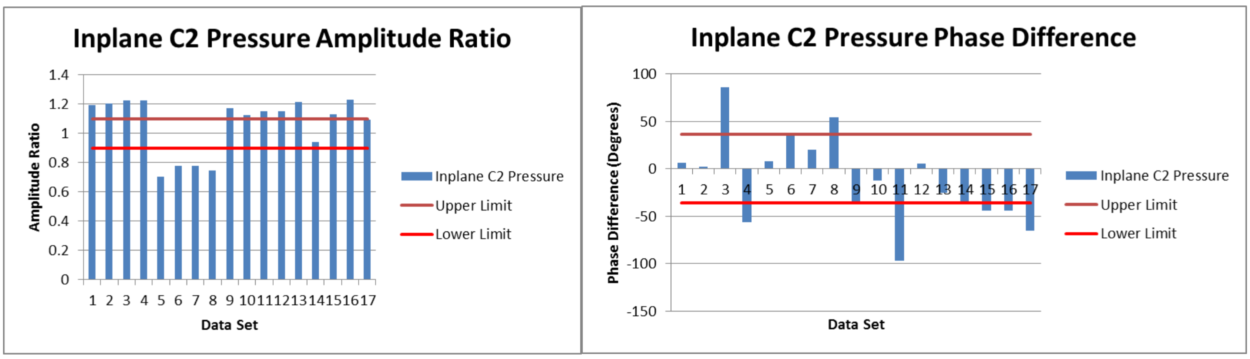


Figure 43 - In-plane Actuator C2 Pressure AR and PD

The Resonator load AR and PD results are shown in figure 44, all of the AR results are within the specified limits. Two of the PD results fall out of these limits, but on the whole, the modelling results for this signal are good.

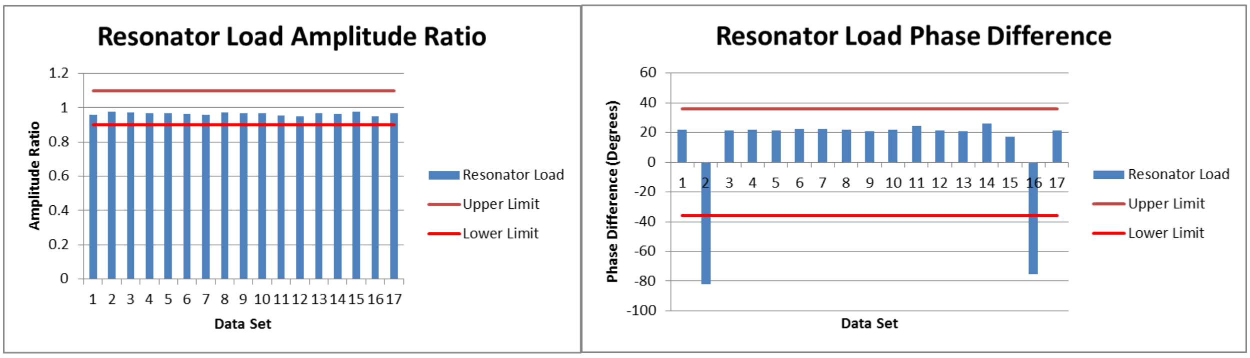


Figure 44 - In-plane Resonator AR and PD

The remaining AR and PD validation results can be found in Appendix 5. The next section summaries the whole of the validation results.

5.2.4 Validation Summary

The in-plane validation results for all of the modelled signals are shown in table 6.

Signal name	NRMSE Average	AR data sets out of limits	PD data sets out of limits
In-plane displacement feedback	7%	0%	0%
In-plane Force	41%	0%	0%
In-plane C1 Pressure	21%	76%	35%
In-plane C2 Pressure	22%	88%	41%
Resonator Load	13%	0%	18%
In-plane Acceleration	29%	0%	0%
C1 Resonator Pressure	8%	35%	35%
C2 Resonator Pressure	7%	24%	35%
C1 Resonator Position	37%	29%	35%
C2 Resonator Position	40%	0%	6%
In-plane Valve Displacement	18%	29%	18%
In-plane Servo Drive	21%	6%	12%

Table 6 - Summary of Validation Signals

The purpose of the modelled system is for it to be used in detecting and predicting machine faults, therefore a certain level of accuracy is required. The current accuracy of the modelling may allow fault detection techniques to be utilised and therefore give the ability of faults to be detected after they have occurred on the LF60. Chapter 6 reviews potential fault detection methods and then uses the in-plane model in conjunction with fault detection techniques, illustrating the revised model operation simulated with a number of actual machine faults.

5.3 Isolation of 4th Stage Valves

This section validates an isolated model of the 4th valve stages to review the potential for fault prediction of the LF60 machine.

An example of the full length time series data for the in-plane force signal is shown in figure 45 with the area of interest highlighted. The end portion of the in-plane force signal can be seen in figure 46 and figure 47 highlighting no instability and instability respectively.

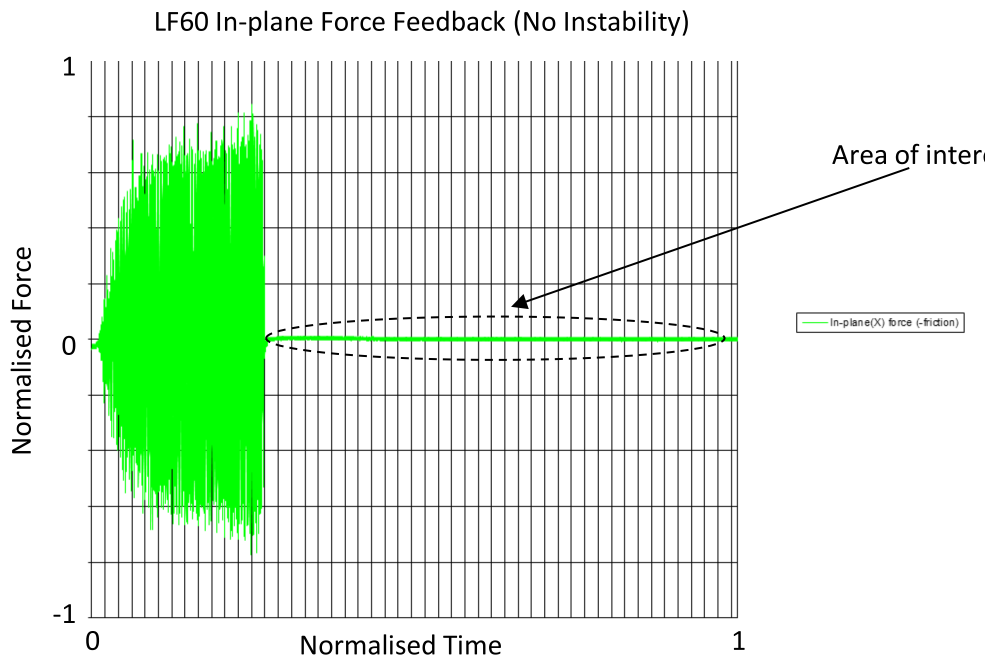


Figure 45 - In-plane Force feedback signal example – illustrating the area of interest

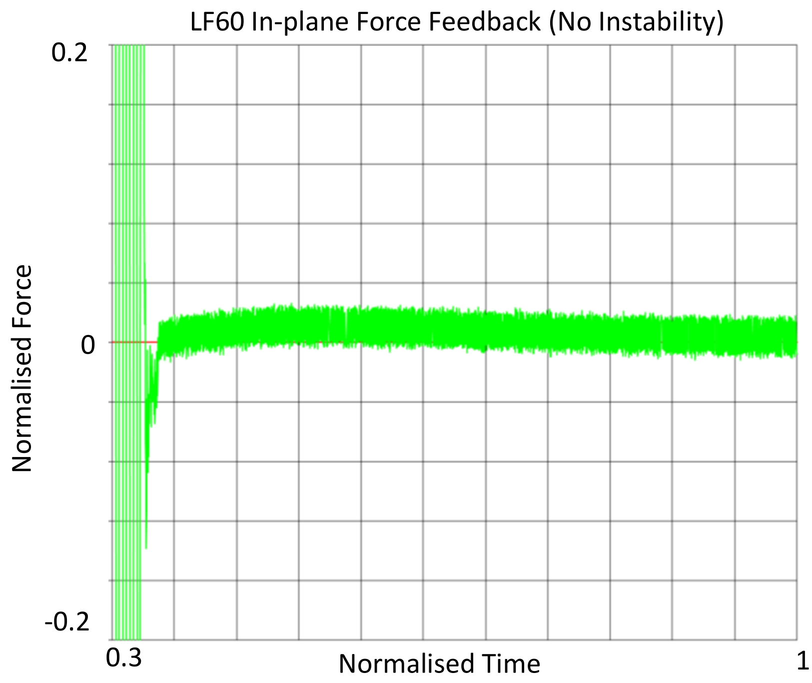


Figure 46 - In-plane Force feedback signal example – No instability

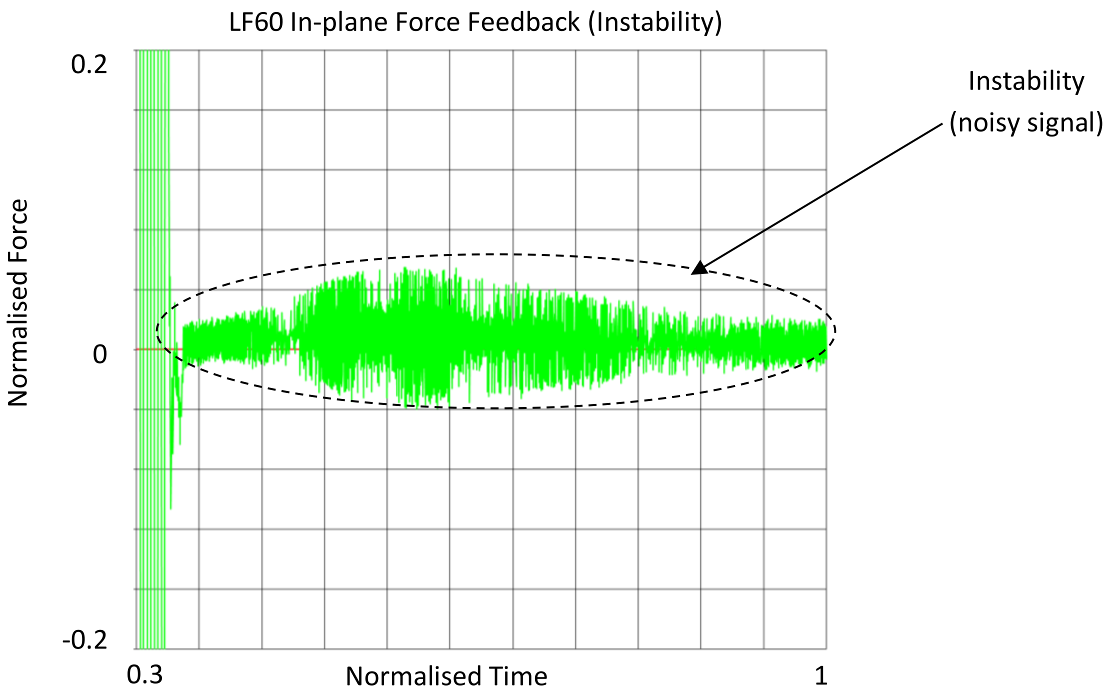


Figure 47 - In-plane Force feedback signal example – instability

5.3.1 Validation Investigation 1: Internal Validation

This section investigates the 4th stage model by using previously welded machine data. The data contains an instability therefore for effective fault prediction the model should indicate significant changes in the output measurement up to and before the instability.

Data from a series of Blisks welded on the LF60 have been used. The 4th stage spool positions have been used as model inputs. On review of the results the model output which correlated well with the instability was the difference in the servo valve A and B flow outputs. Results of this can be seen in figure 48; the graph shows the average flow difference between the valves across each of the 45 Blisks (each Blisk contain 24 blades).

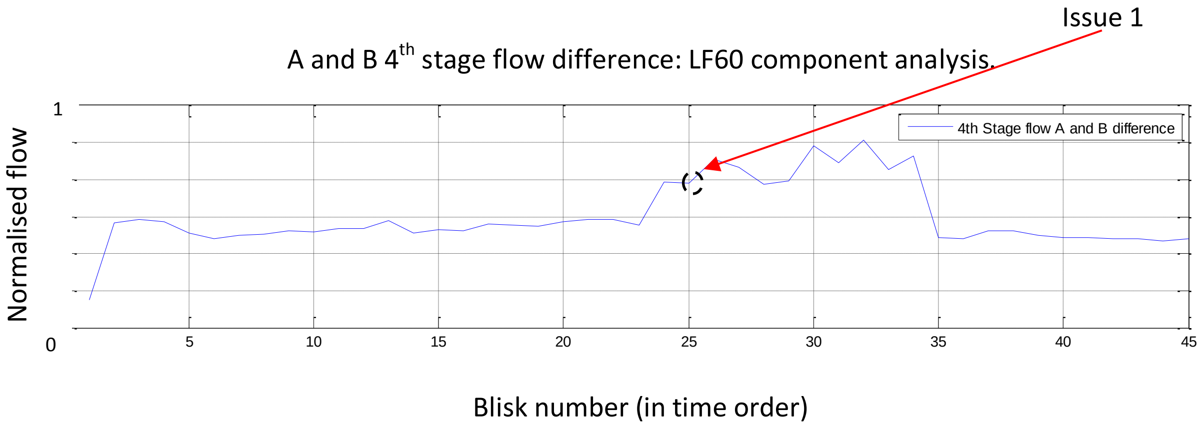


Figure 48 - Average valve flow difference (normalised)

Analysing the results of figure 48 show a number of interesting findings:

- Over time, the flow difference between the 4th stage valves slowly increases

This is thought to be due to wear associated with the valve use over time, as parts are welded the high flows through the servo valve orifices could cause an increase of the spool clearances (this may be at an uneven rate i.e. one valve could wear at a higher rate than the other)

- Issue 1, pinpoints an instability occurrence in the data (on the 25th Blisk).

The increased flow difference was caused due to a modification of a valve. During this time an instability occurred, therefore it is conjectured that the likelihood of an instability may be increased with greater flow difference between the servo valves.

Therefore this model could be used to track the flow difference between the valves, signalling to the user high flow difference conditions which would prompt for action to be taken before servo valve instability occurs.

5.3.2 Validation Investigation 2: Tests to Induce a Fault

To try to recreate a flow difference between the separate valves (recreating the instability conditions), an external fan was placed facing one side of the in-plane valve arrangement, see example in figure 49. This was to create a cooler valve, introducing a thermal difference between the valves to affect the material which may induce a flow difference between the valves.

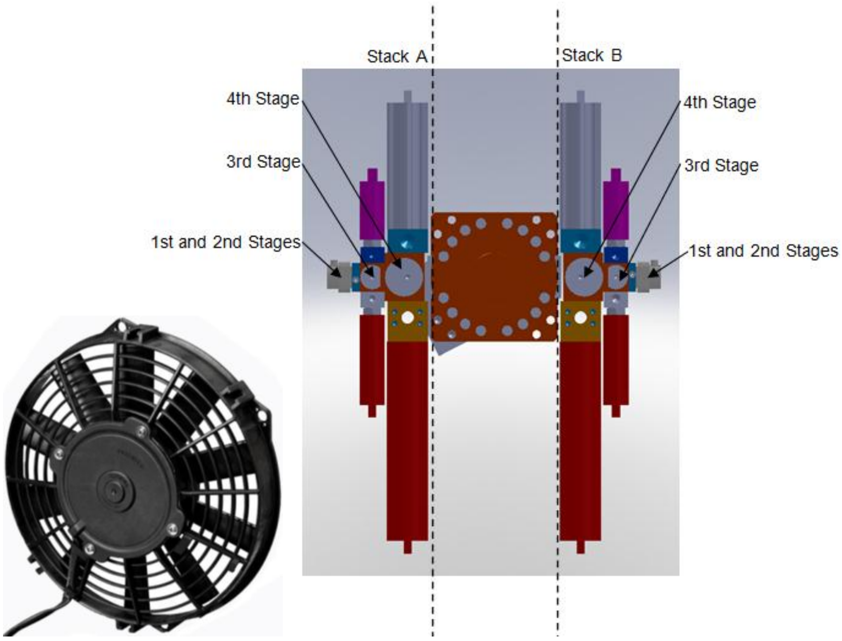


Figure 49 - In-plane valves and external fan example

Three validation welds were made with different valve temperatures, these variations are shown in table 7.

Experiment Number	Temperature of valve A	Temperature of valve B	Temperature difference (B-A)
1	42.11°C	45.48°C	+3.37°C
2	47.99°C	50.22°C	+2.23°C
3	51.97°C	46.38°C	-5.59°C

Table 7 - Temperature Variation Results

The time series results from each of the temperature variation tests are shown in figure 50.

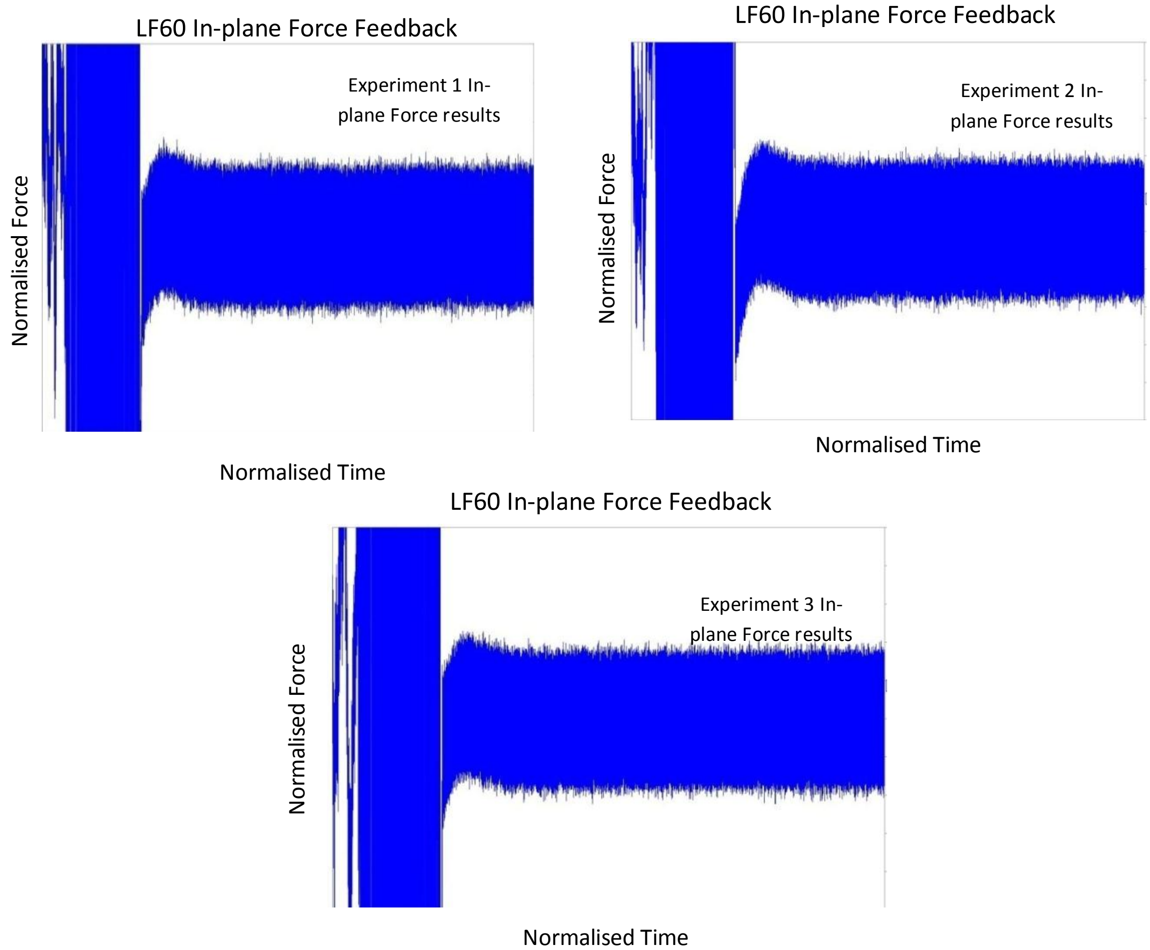


Figure 50 - Temperature variation results

From the observed results no instabilities occurred during the welds, executing the weld data through the 4th stage model produced varied flow difference results which are displayed in figure 51. Figure 51 shows 10 welded specimens, the initial three are the temperature variation tests which include the additional temperature monitor on valve A. The other 7 welds are a random sample taken of previously welded data (previously valve A did not have additional temperature monitoring).

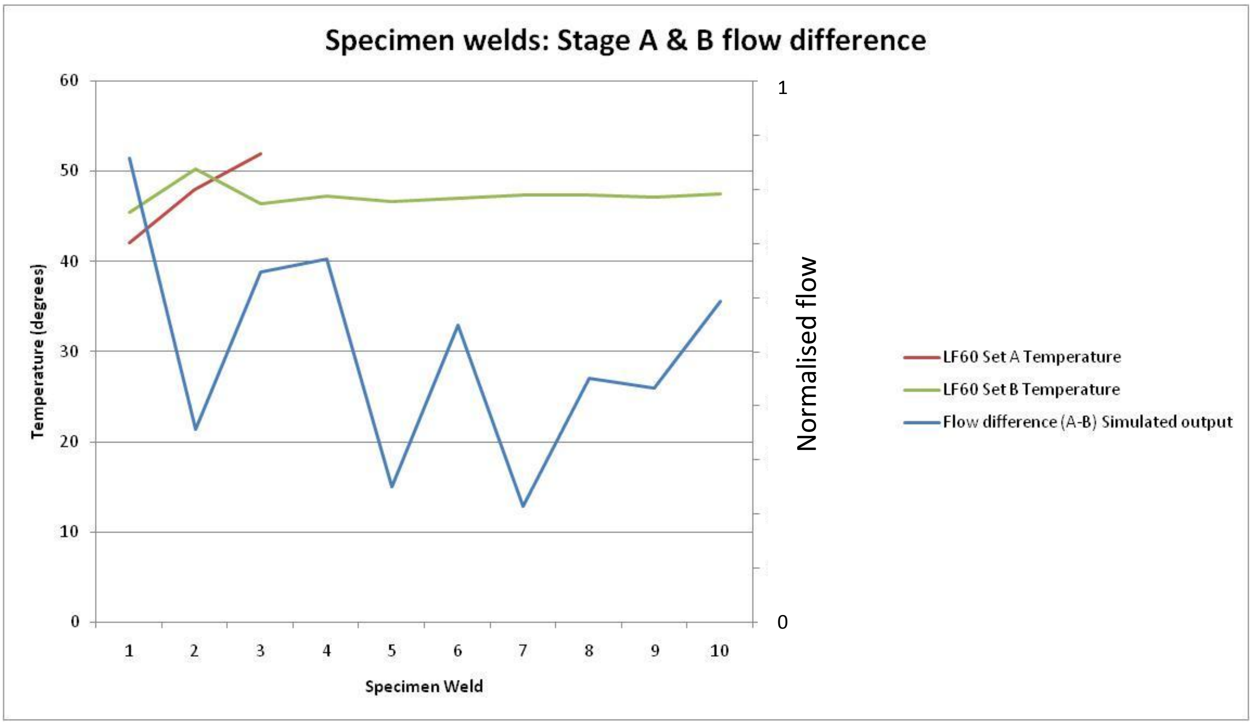


Figure 51 - Graphical Temperature variation results

Therefore the results for the second validation investigation are inconclusive as a change in flow was observed over the temperature validation experiments, but it was minimal and thus did not create an instability on the signal.

5.3.3 Summary

To conclude the 4th stage model validation, the 1st investigation did show a positive correlation of flow differences with in-plane instabilities – Thus linking the increased possibility of an instability with an increased flow difference between the set of valves.

The 2nd investigation did not show any instability when trying to re-create the flow difference; this could have been due to a number of reasons:

- A larger sample size of welds could be needed
- A more effective way of directly influencing the flow difference between the valves would be more appropriate

5.4 Conclusion

Chapter 5: Validation has reviewed the in-plane modelling validity in order to answer the following research questions:

R1: *Can an analytical model be developed to accurately represent a complex physical electro-hydraulic system?*

A model of the in-plane system for the LF60 has been developed in chapter 4. The system was modelled from first principles using Matlab and Simulink to create a multiple stage dynamic servo valve model thus answering the first research question. The model represents the complex physical electro-hydraulic in-plane axis, its accuracy has been reviewed in chapter 5, in order to answer research question 1.

To use the model to diagnose and predict the actual machine faults, the modelling and therefore the actual systems representation would need to be accurate. The validation compared all the measurable machine and model signals, across these signals the average NRMSE is 22%, the average number of AR signals out of tolerance is 24%, and the average number of PD signals out of tolerance is 20% (averaging values can be found in table 6 on page 81). Due to the dynamics of the system the modelling overall accuracy is reduced, therefore the model would be suitable for fault detection but unsuitable for fault prediction.

To handle fault prediction a sub model was developed in Section 5.3 isolating the 4^{th} stage valves. This enabled the internal valve flows to be calculated during a weld

Chapter 6 outlines how the in-plane model can be used for fault detection, demonstrating its use with a number of fault cases.

References

1. **Ramdani, N. and Ojalvo, J.** 2003. *A software for validating complex systems dynamic models: A case study in building thermal physics*, Centre d'Etude et de Recherche en Thermique, Energetique et Systemses, UPRES-EA 3481.
2. **Agilent Technologies.** 2000. *The fundamentals of signal analysis*. Printed in U.S.A. 6/00 5952-8898E

Chapter 6: Fault Detection, Isolation and Prediction

6.1 Introduction

In this chapter a model-based fault detection and isolation (FDI) strategy is developed for the in-plane system which was modelled in chapter 4. Utilising the developed model for FDI will bring about the following benefits:

- Additional monitoring of the LF60 complex hydraulic in-plane system. This is the system most likely to cause production issues.

- The potential reduction of scrapped components therefore saving money and unforeseen downtime.

The in-plane model developed in chapter 4 will be used to describe the behaviour of the actual system under fault free operation. Therefore in comparing the model and actual system outputs any inconsistencies would signify the occurrence of a fault. As concluded in chapter 5, the model validation highlighted that the in-plane modelling would not be sensitive enough to predict faults only detect them.

The chapter is outlined as follows: Section 6.1.1 reviews typical hydraulic faults and the faults which are common to the LF60 system are examined in Section 6.1.2. Various fault detection approaches which are commonly used in the literature are explained in Section 6.1.3. Section 6.2 applies the most appropriate fault detection approach to the in-plane model, which is evaluated against real data in Section 6.3. The model for fault prediction is reviewed in Section 6.4 and the chapter is concluded in Section 6.5.

A paper on this chapter has been published in the Eighth International Conference on Systems (ICONS'13) [P2].

6.1.1 Typical Hydraulic Faults

Different types of faults can occur in hydraulic systems. Common faults found are:

- Excessive fluid temperatures
- Oil contamination
- Leakage

Excessive fluid temperatures are problematic due to the viscosity changes of the oil and therefore impact on system performance. This is usually due to a reduction in the system's capacity to remove heat, or increases in the heat generation of the various components. Excessive temperatures can lead to component damage, acceleration of system wear, and degradation of the oil [1].

Oil contamination can be from air, water, or various elements found within the system or external contamination. These contaminants can enter hydraulic systems through pump suction ports, low reservoir levels, or component wear debris. Servovalves are particularly sensitive to oil contamination [2].

Flow reduction in a hydraulic system would lead to a slower performing system, pumps, valves, or actuators would performance at a reduced capacity therefore possibly not meeting the system output requirements. This could be due to an increase of internal leakage due to wear [1].

Components in a hydraulic system can fail gradually or suddenly. The fault detection method applied to the model aims to capture the common faults which occur on the LF60, and then isolate their cause so a quick system recovery can be made.

6.1.2 LF60 Faults

A wide range of different faults can occur on a number of hydraulic or electrical components utilised on the LF60 Machine. This thesis is only concerned with faults occurring on the LF60 in-plane system as this is the most critical system; faults on this system can cause the most detrimental impact to the component and this system is the one in which the majority of faults appear[5].

The faults which have contributed to system downtime or the loss of a component are summarised below;

1. This first fault appeared at the start of the welding phase, the issue was present until the holding phase, as shown in figure 52. The machine limits captured this fault therefore production was halted until the problem was resolved. The cause of this issue was due to a faulty relief valve which caused the input pressure to the valves to fluctuate which therefore caused fluctuations in the in-plane position signal. Once the relief valve was replaced the issue was resolved [16].

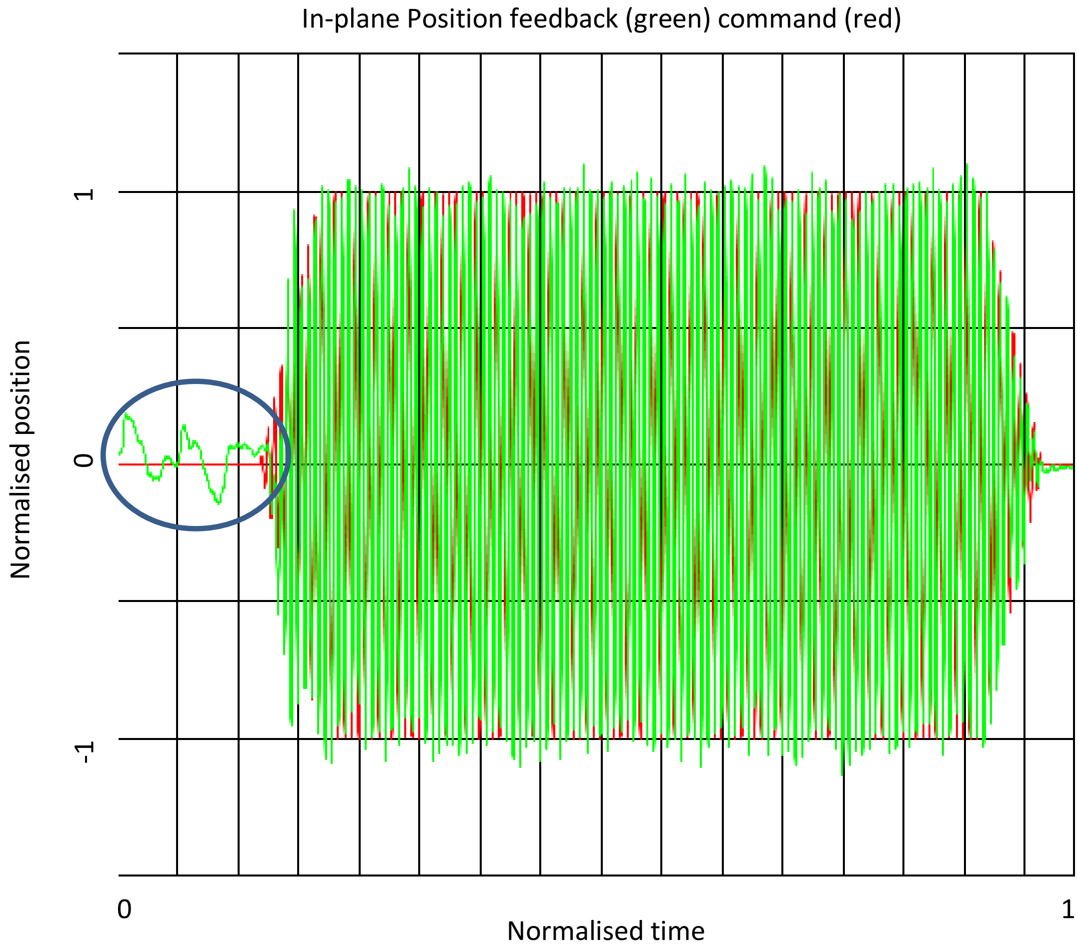


Figure 52 - Start-up oscillation

[5] Analysing previous RR fault timeline data created by Graham Colin 2011 which reviews all the previous faults and system download on the LF60 - Confidential data so the information is not included.

2. This next fault appeared during the holding phase of the welding, as depicted in figure 53. During a series of production welds this issue was not captured by the machine limits which were in place, and only noticed upon manual inspection of the data. This fault was due to increased wear on the in-plane valves, which caused the internal spool overlap dimensions to decrease, which therefore lead to an increased difficultly for the servo valve to maintain zero pressure around the null position. Once a new set of valves were placed on the machine the issue was resolved [3].

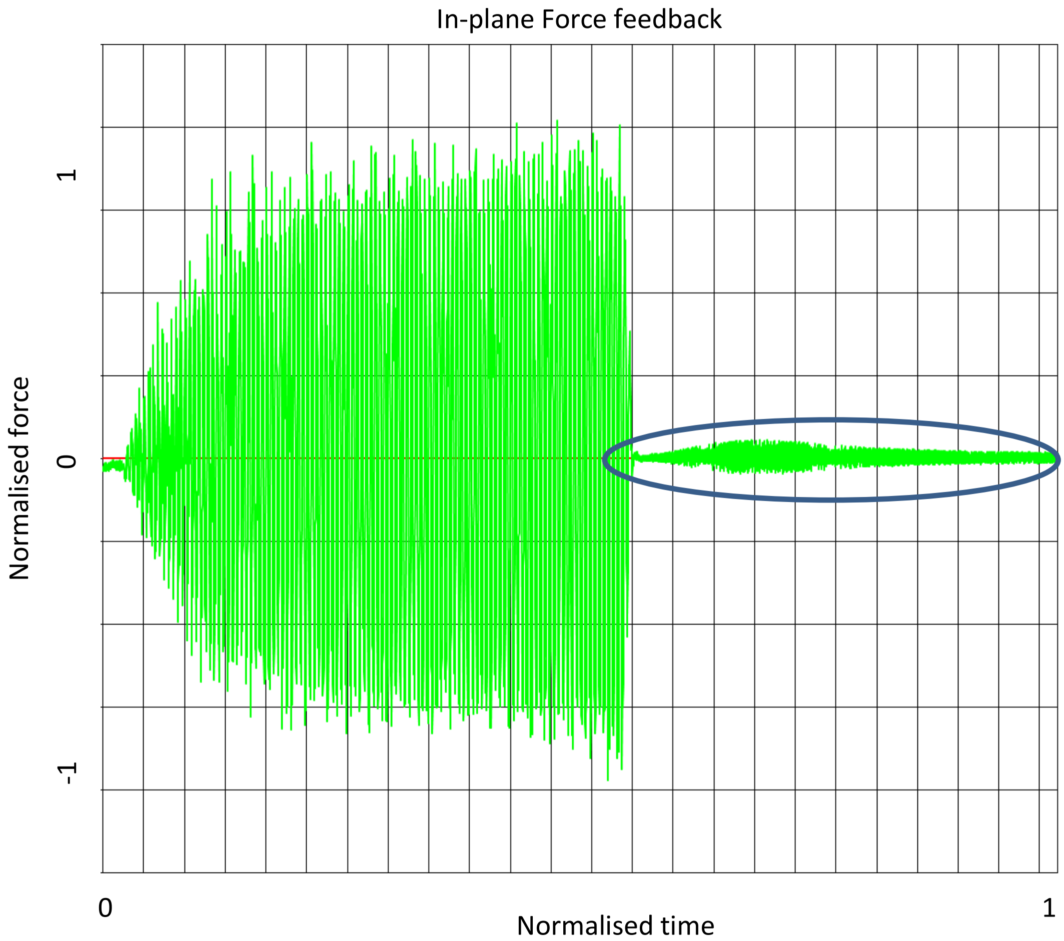


Figure 53 - Holding force oscillation

3. This fault appeared as a low frequency oscillation occurring during the holding phase of the welding, as shown in figure 54. During a series of production welds, this issue occurred on four welds, but the first three were of a lower magnitude and thus not captured by the machine limits. The machine was alerted to the issue after the third weld. This issue was caused

by a loose electrical wire, once properly connected the issue disappeared [16].

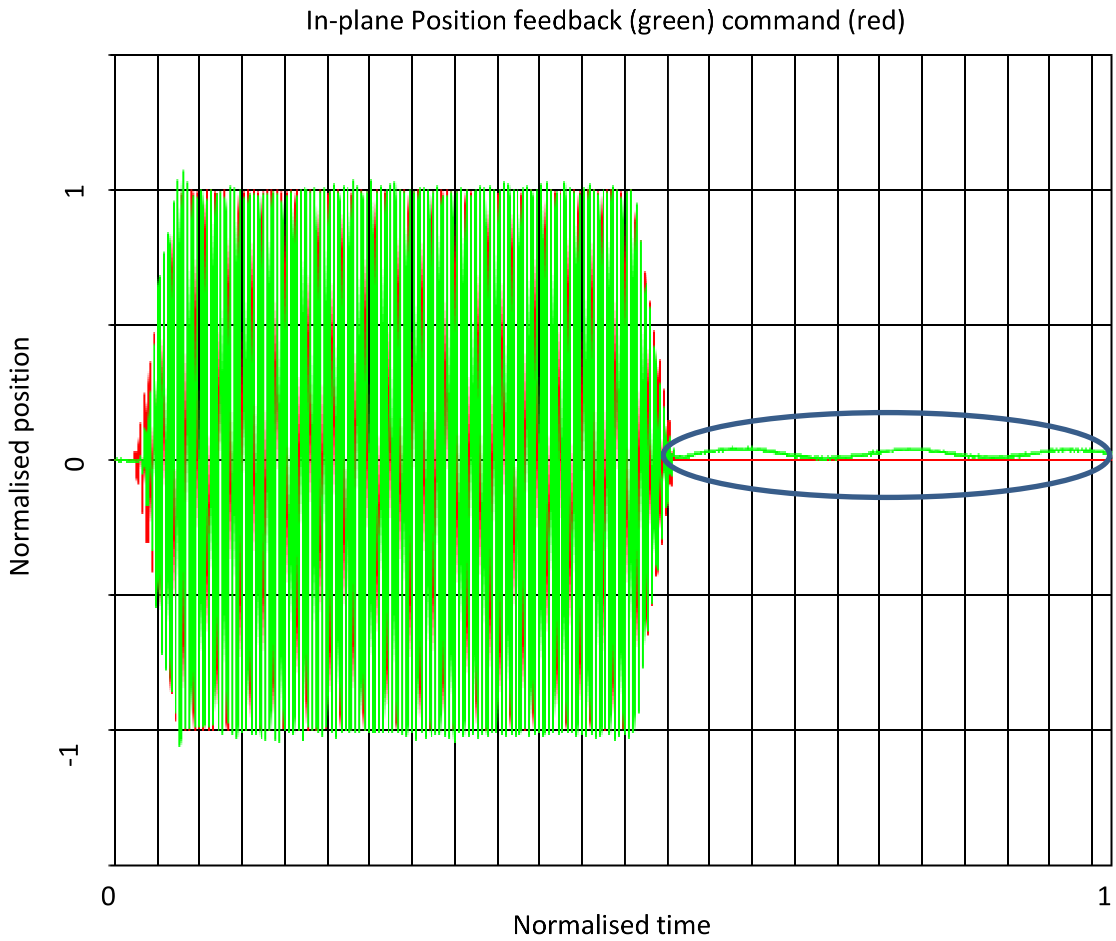


Figure 54 - Low frequency Holding oscillation

4. The final fault appeared as a random spike during the oscillation phase of the weld, as shown in figure 55. During a series of production welds, this issue was not captured by the machine limits which were in place, and therefore the full Blisk was welded and this fault was noticed upon a manual review of the data. After inspection the cause of the fault was found to be due to a loose connection causing an intermitted signal spike, propagated through a number of the machines signals. The loose connection was resolved and the issue disappeared [17].

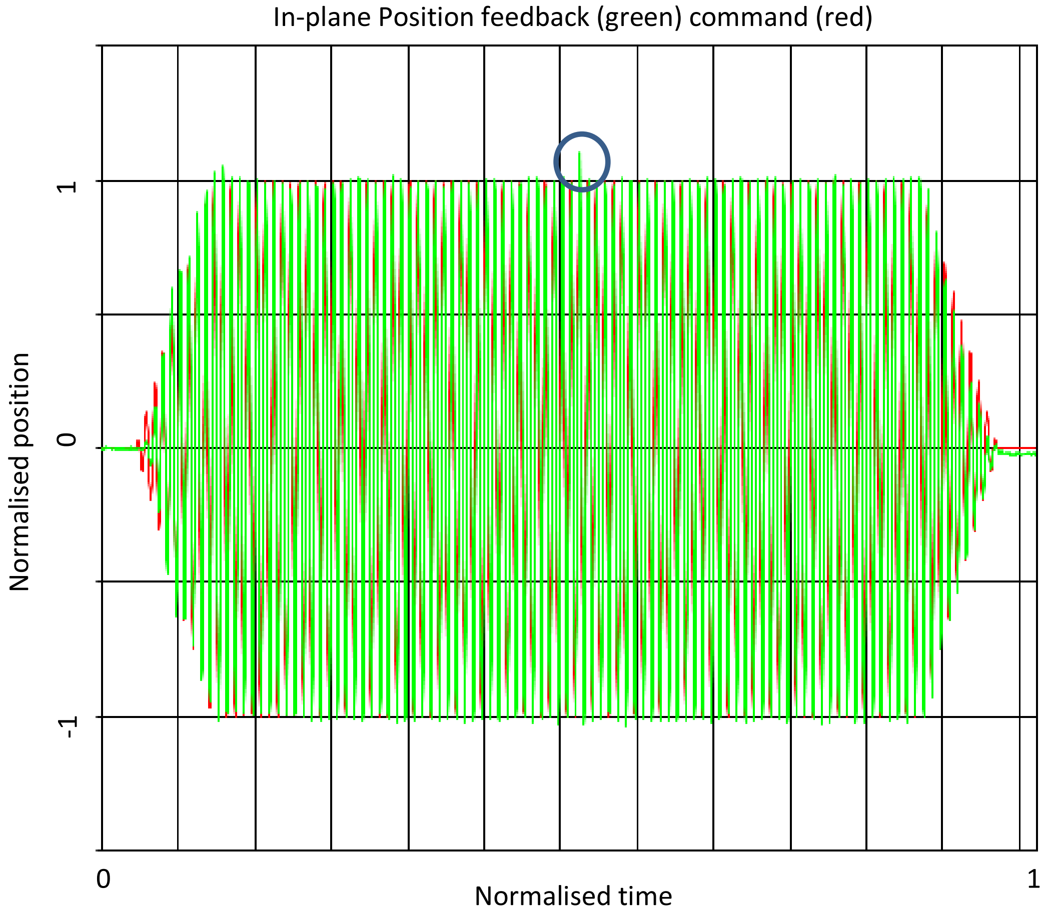


Figure 55 - Position spike

All these issues can be detrimental to the positional accuracy of the welded blade and could cause a scrapping of the welded component. Therefore the detection of any of the above issues in their first instance would be a crucial aspect of the fault detection scheme chosen.

6.1.3 Fault Detection Approaches (Residual Generation Schemes)

A number of fault detection approaches exist in the literature. A classification of these different approaches can be seen in figure 56.

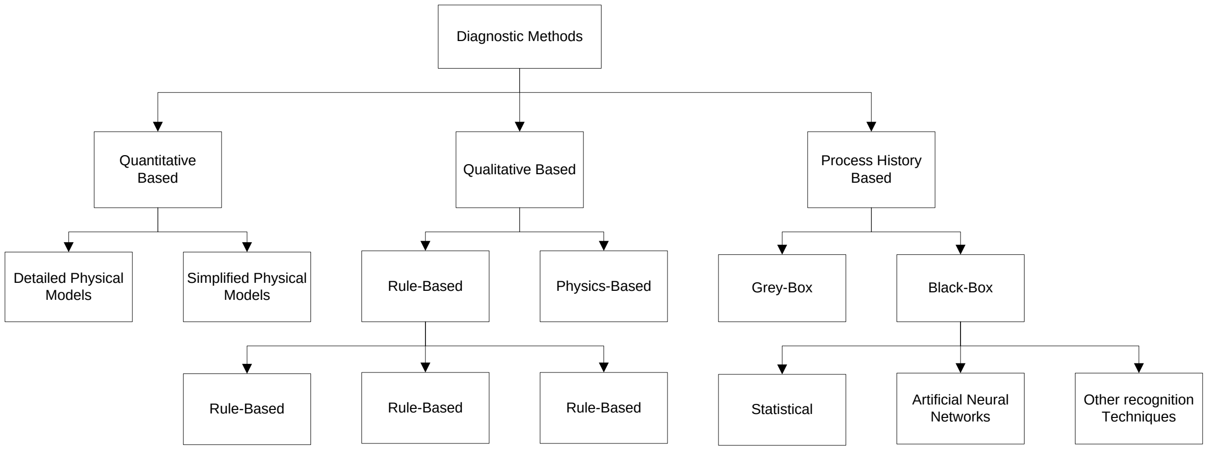


Figure 56 - Classification of the diagnostic system [4]

Quantitative diagnosis methods involve creating a mathematical model redundancy with the use of physical models to generate residuals that can be used for isolating process failures. These can be detailed or simplified physical models.

Qualitative diagnosis methods can be rule based, or qualitative physics based. Rule based systems involve systems derived from expert knowledge, first principles, or limit checks.

Process history based diagnosis methods are used when a prior knowledge of the process is not known therefore input-output (black box) relationships are developed using statistical, neural network, or similar pattern recognition techniques. Grey box methods use process data to determine physical model parameters by using estimation methods.

Given the availability of a system model (developed and validated in chapters 4 and 5 respectively) the diagnosis system used will be qualitative, using a detailed physical modelling. A number of model-based fault diagnosis methods can be found in the literature [4-6], the main two are parity equation methods, and observer based approaches, these different methods are discussed in the following subsections.

6.1.3.1 Parity Equation Methods

The Parity Equation Method involves providing a proper check of the parity (consistency) of the measurements for the monitored system (first proposed by [7]). Mathematical models describing the relationships between system variables are used to describe the input-output or space-state characteristics of the system, the rearrangement of these gives the parity equations [4]. Output of the parity equation in theory should be zero mean, but in reality due to model inaccuracies, measurement and process noise, the output will be nonzero. Parity methods are similar to observer methods but usually designed more intuitively. Figure 57 shows two methods for parity generation, an output error method and the equation error method.

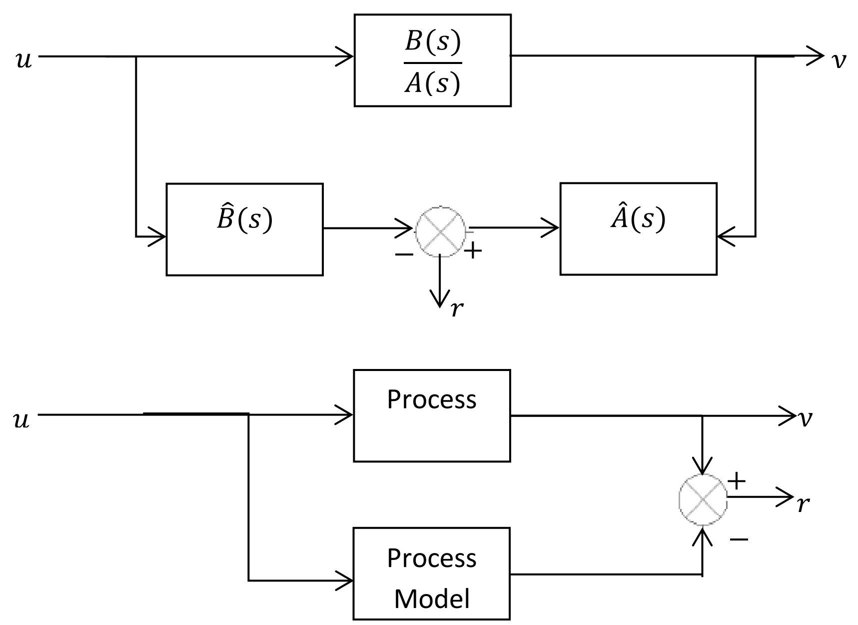


Figure 57 - Parity equations for fault detection: Equation error method (upper), Output error method (lower) [8]

6.1.3.2 Observer Approaches

Reconstructing the outputs of a system from measurements using the estimation error with observers or Kalman filters is another commonly used approach for fault diagnosis [9]. With the observer approach the estimation error can be considered as the residual, in order to detect and isolate faults. For stochastic systems, the Kalman filtering technique can be used, which enables noise to be factored into the approach [10]. State estimation is improved with the use of Kalman filters due to the processing of all available measurements regardless of precision to estimate the current variable of interest.

For example, take the system state and measurement equations (1) and (2) respectively:

$$\dot{x} = Ax + Bu + Gw \tag{1}$$

$$y = Cx + Du + Hw + v \tag{2}$$

where u is the system input, the process noise is represented by w, and the measurement white noise is represented by v with $E\ (ww^T) = Q$, and $E\ (vv^T) = R$. The state and estimation noise is uncorrelated i.e. $E\ (wv^T) = 0$. The Kalman filter equation can provide the optimal estimate of y termed $\hat{y}$:

$$\hat{x} = A\hat{x} + Bu + L(y - C\hat{x} - Du) \tag{3}$$

$$\hat{y} = C\hat{x} + Du \tag{4}$$

The calculation of L is chosen to trade off fault sensitivity to the likelihood of false alarms using engineering experience. Figure 58 shows the Kalman estimator, which uses the known inputs u and the measurement y to generate the output and state estimates $\hat{y}\ and\ \hat{x}$.

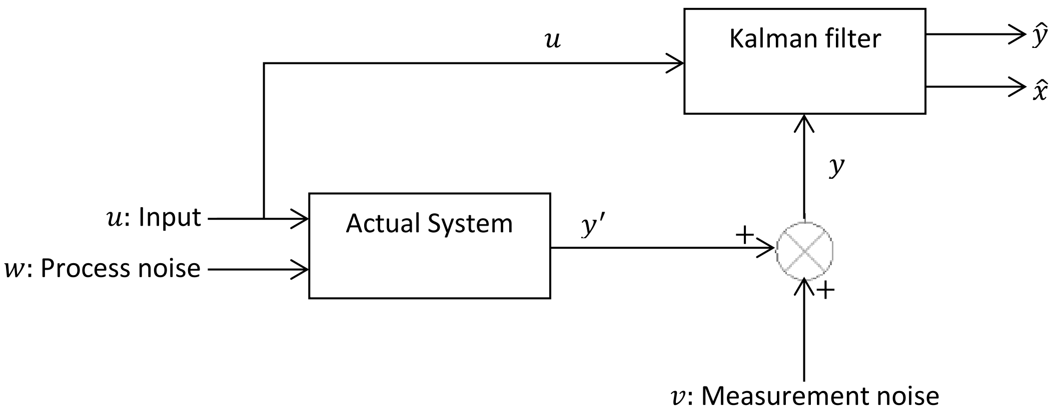


Figure 58 - Observer approach: Kalman estimator

6.1.3.3 Fault Detection Approach Summary (Residual Evaluation)

Each of the discussed approaches involves the creation of a residual (or series of residuals) which need to be analysed further to provide indication and the possible isolation of faults. Residual evaluation can be done using a constant threshold or an adaptive threshold. Constant threshold residual evaluation has a number of disadvantages. Due to the inclusion of noise, or uncertainties in models false alarms can be triggered. Therefore adaptive thresholds which take into account any modelled inaccuracies or noise can enable better fault detection, and the reduction of false alarms. Section 6.2 outlines the proposed fault detection scheme reviewing the generation and evaluation of residuals for the model based system fault detection system.

6.2 Fault Detection Scheme

The fault diagnostic method used in this thesis will be of the qualitative type with detailed physical modelling of the system. Within the diagnosis method an observer based approach will be used. The in-plane system model developed in chapter 4 will act as an observer providing the mathematical model. Residual generation will be made by comparing the measured values of the system outputs y_i, with the corresponding analytically computed values $\widehat{y_i}$:

$$r_i = y_i - \widehat{y_i} \tag{5}$$

Figure 59 outlines a flow diagram of the Fault diagnosis system, indicating residual generation and evaluation in order to detect and isolate faults.

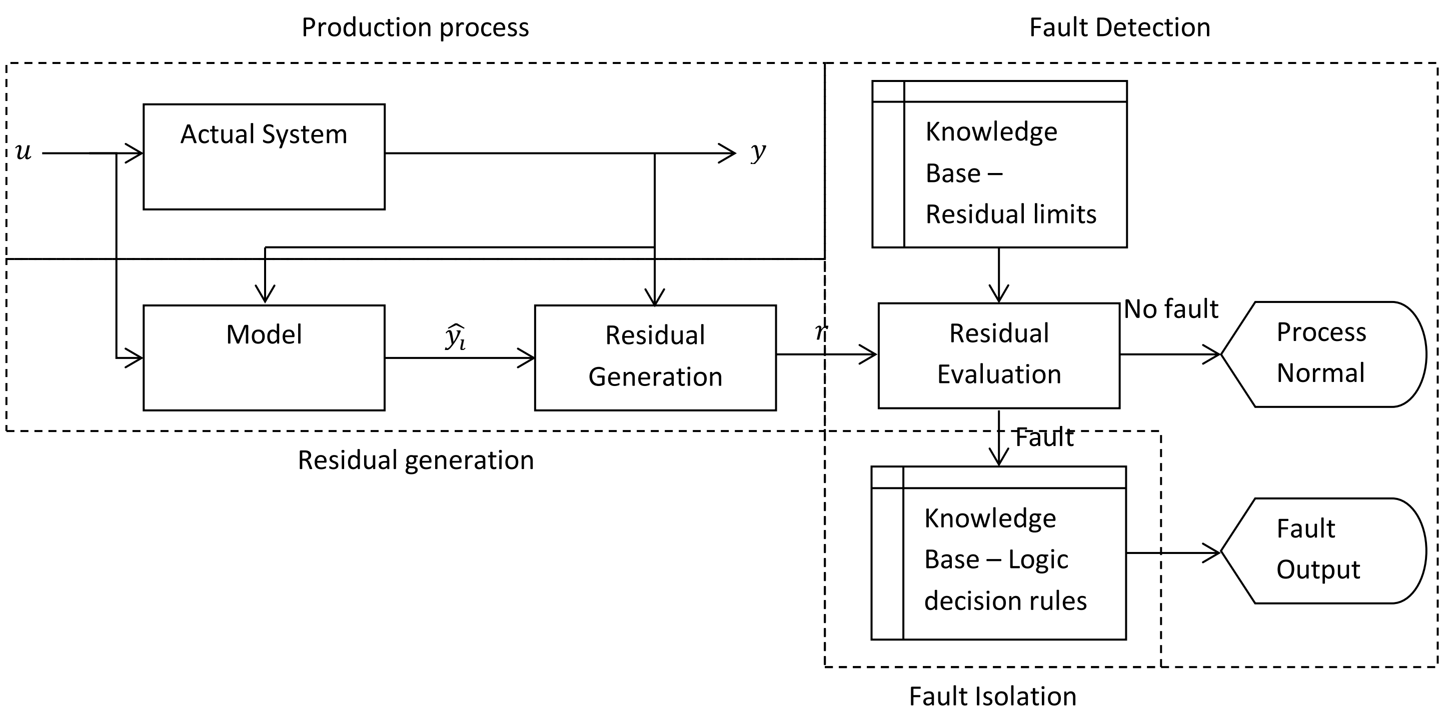


Figure 59 - Fault diagnosis flow diagram

Once a residual has been generated, the residual would need to be evaluated to see if a fault is present or not. Various forms of residual evaluation exist in the literature some of which include residual threshold setting based on the minimal detectable failure [11]; posterior probabilities to process information in order to detect faulty circuits [12]; the use of fuzzy logic enabling the incorporation of human operator knowledge to interoperate the residuals [13]; and probabilistic methods based on likelihood ratios [14]. The residual limits in this thesis will be created by using previous fault free data executed through the model, in order to capture the maximum residual limits for fault free conditions. Therefore creating adaptive residual limits defined from previous fault free data, similar to [15]. Due to the different components welded on the LF60 the residual limits will be component specific, therefore a number of knowledge based data files will be stored which hold residual limits for each variable and component. In the presence of a fault the residual signal will appear high i.e. $r_i > residual\, limit$ at that time signal. The creation of the adaptive residual limits is outlined in Appendix 6.

The use of adaptive residual limits defined from previous fault free data will allow for any compared signals (model vs. new data) which deviate more than normal, outside of the modelling noise, disturbances, and inaccuracies to be picked up and therefore flagged by the model alerting to a fault, or a change in system performance. On the detection of a residual breach the system will decide on the type of fault, its cause, location, and possible solutions given a knowledge base of logical rules defined from previous fault occurrences. A flow diagram of the logical rules can be seen in figure 60. This logic diagram embodies expert knowledge of previous faults. The red outputs are the previous faults which have been identified, and the corresponding residual inputs which would trigger the fault can be tripped throughout any phase of the weld.

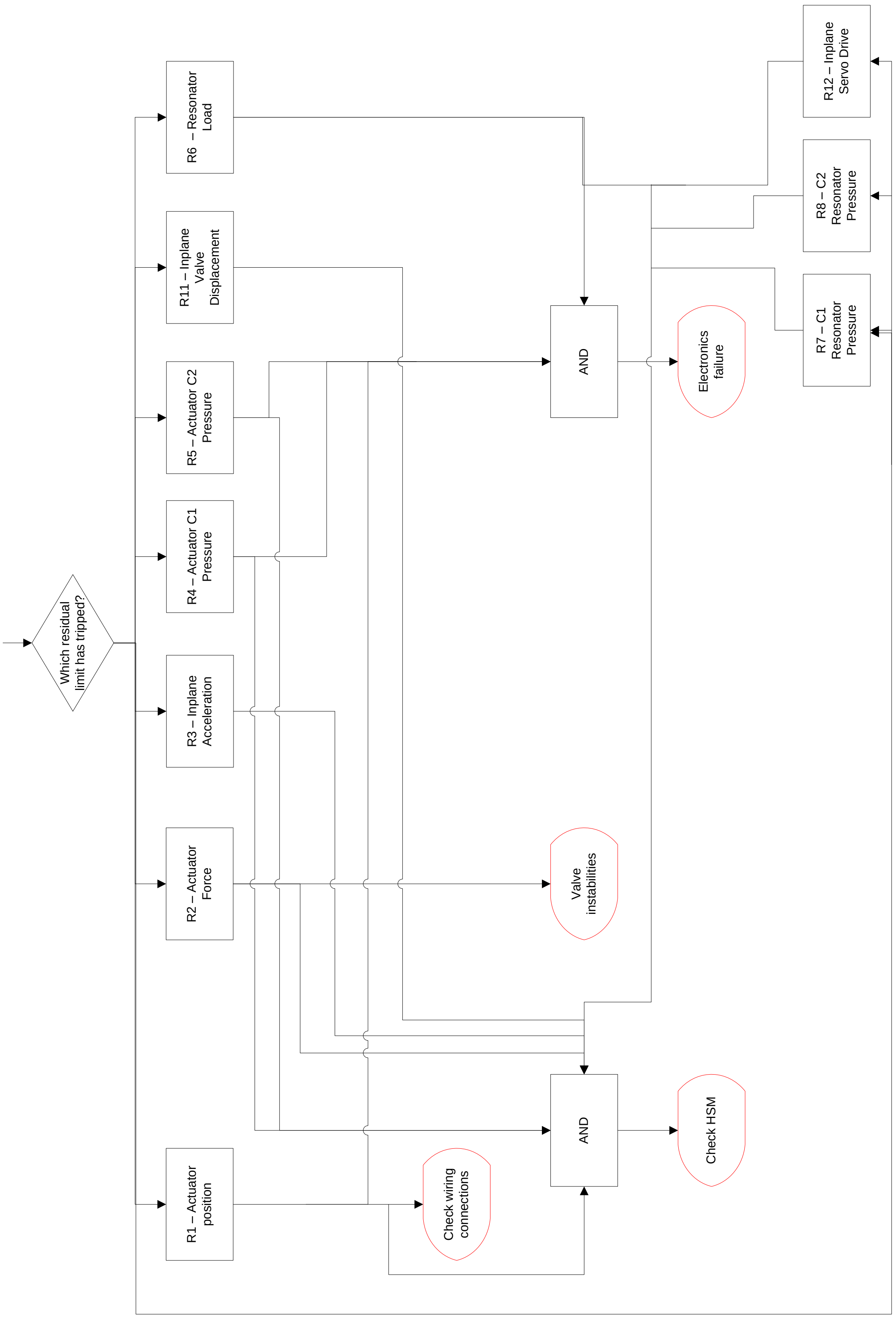


Figure 60 - Flow diagram of the Logical decision process

Section 6.3 implements the fault detection scheme and evaluates it using a number of fault cases.

6.3 Testing the Fault Detection Scheme

In order to evaluate the FDI model the four faults which have previously occurred during production welding as identified in 6.1.2 will be used as test cases, as a recap these faults were:

1. Start-up oscillation: positional signal
2. High frequency oscillation during the hold time: force signal
3. Low frequency oscillation during the hold time: positional signal
4. Random spike during the oscillation phase: positional signal

These fault cases will be simulated. The objective of the fault cases is to determine whether the modelling and fault diagnosis methods used would have detected the occurrence of the faults on the LF60 system.

6.3.1 Fault Case 1: Start-up Oscillation

The start-up oscillation shown in figure 52 was caused by a faulty relief valve [16], and the machine detected this issue therefore production was immediately halted. Therefore for additional benefits the fault detection model would not only detect the fault but also isolate the issue by the model informing the operators of its cause and possible solution.

Simulating a non-faulty component of the same type through the FDI model yields the outputs shown in figure 61. The upper figure compares the actual (fault free) position with the model output, the 2nd figure shows the residual signal and adaptive limits. The 3rd figure indicates any trips of the adaptive residual limit by the residual, and the lower figure indicates detection of a fault on the signal. The fault detection signal only trips if the limit trip signal is triggered and remains triggered for a predefined persistence of 3ms. This is to further reduce false fault detections.

The adaptive limits are based on previous fault free data, for their creation see appendix 6.

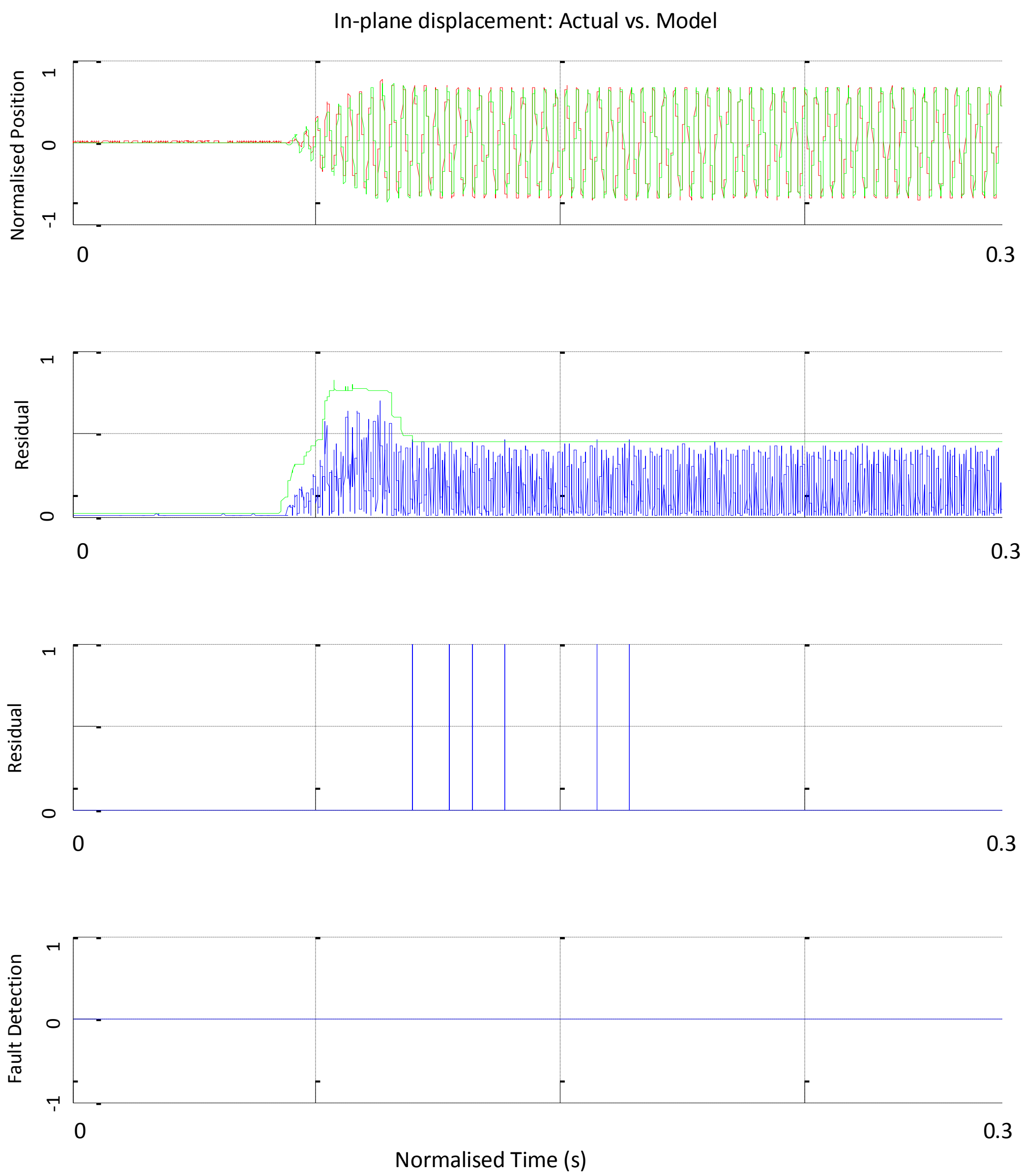


Figure 61 - Start-up Oscillation, Fault detection with the residual generation method (fault free)

Figure 62 shows the FDI model simulated with the start-up oscillation fault. The limit trip signal is tripped immediately and a number of times throughout the simulation – therefore the fault detection signal trips also and stays high from the start of the simulation. This simulation shows an effective capture of the fault using the FDI model. Using the logic defined in figure 60 (section 6.2), the model outputs an indication to the user to “Check hydraulic supply manifold” after detecting the presence of the fault occurrence on the relevant signals. The other signals which are relevant to the isolation of this fault during the fault occurrence are shown in Appendix 7 – Fault Case 1.

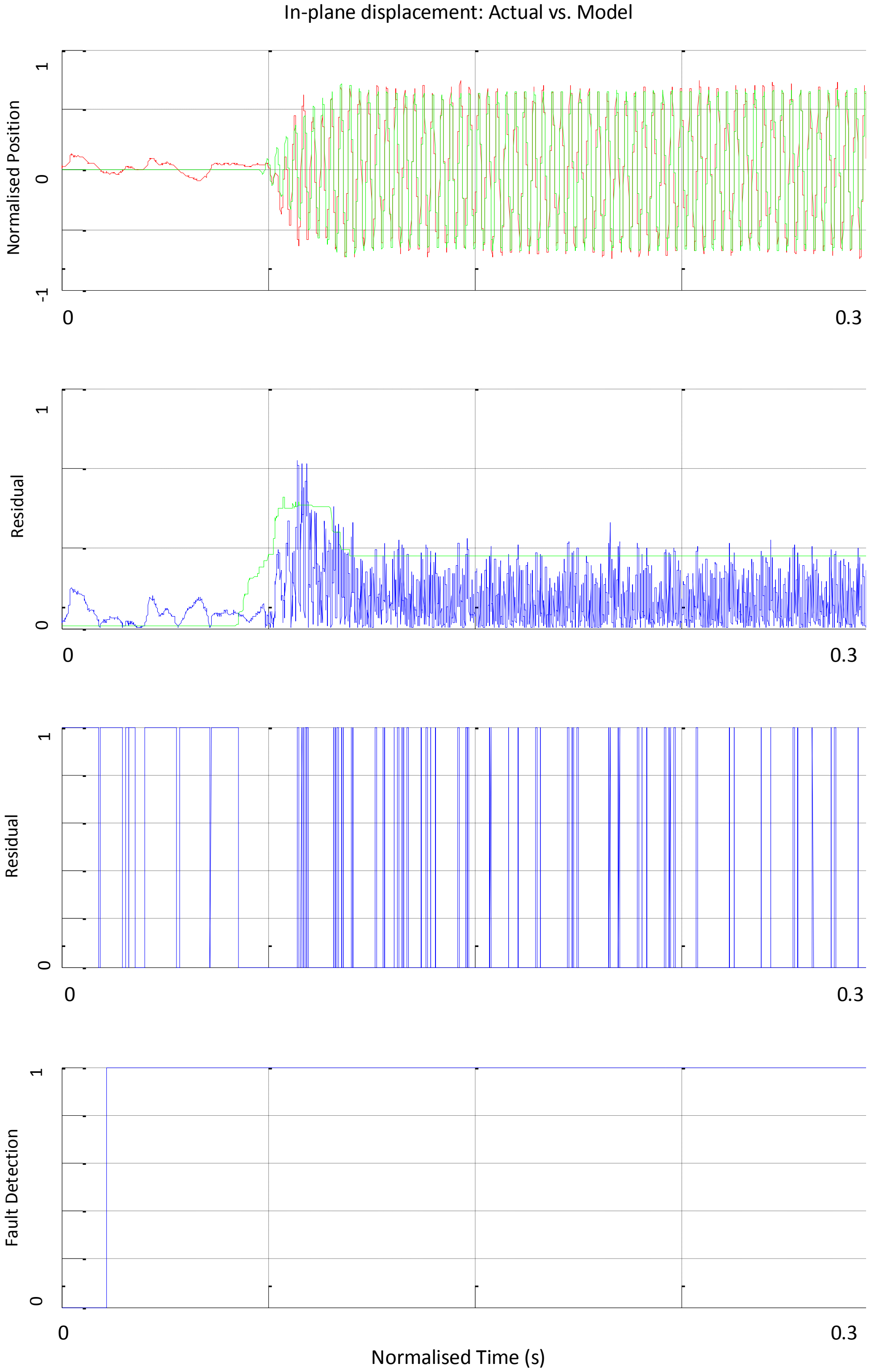


Figure 62 - Start-up oscillation, Fault detection with the residual generation method (fault)

6.3.2 Fault Case 2: Force Holding Oscillation

The in-plane force holding oscillation of figure 53 was only captured during a manual review of the data post Blisk completion. Therefore the immediate detection of this type of fault would be of great benefit to potentially saving the scrapping of the Blisk and rectifying the issue immediately. On simulation of the fault through the FDI model, the model and residual limits are sensitive enough to capture the oscillation and therefore indicate the presence of a fault, as shown in figure 64.

FDI model simulated with fault free data:

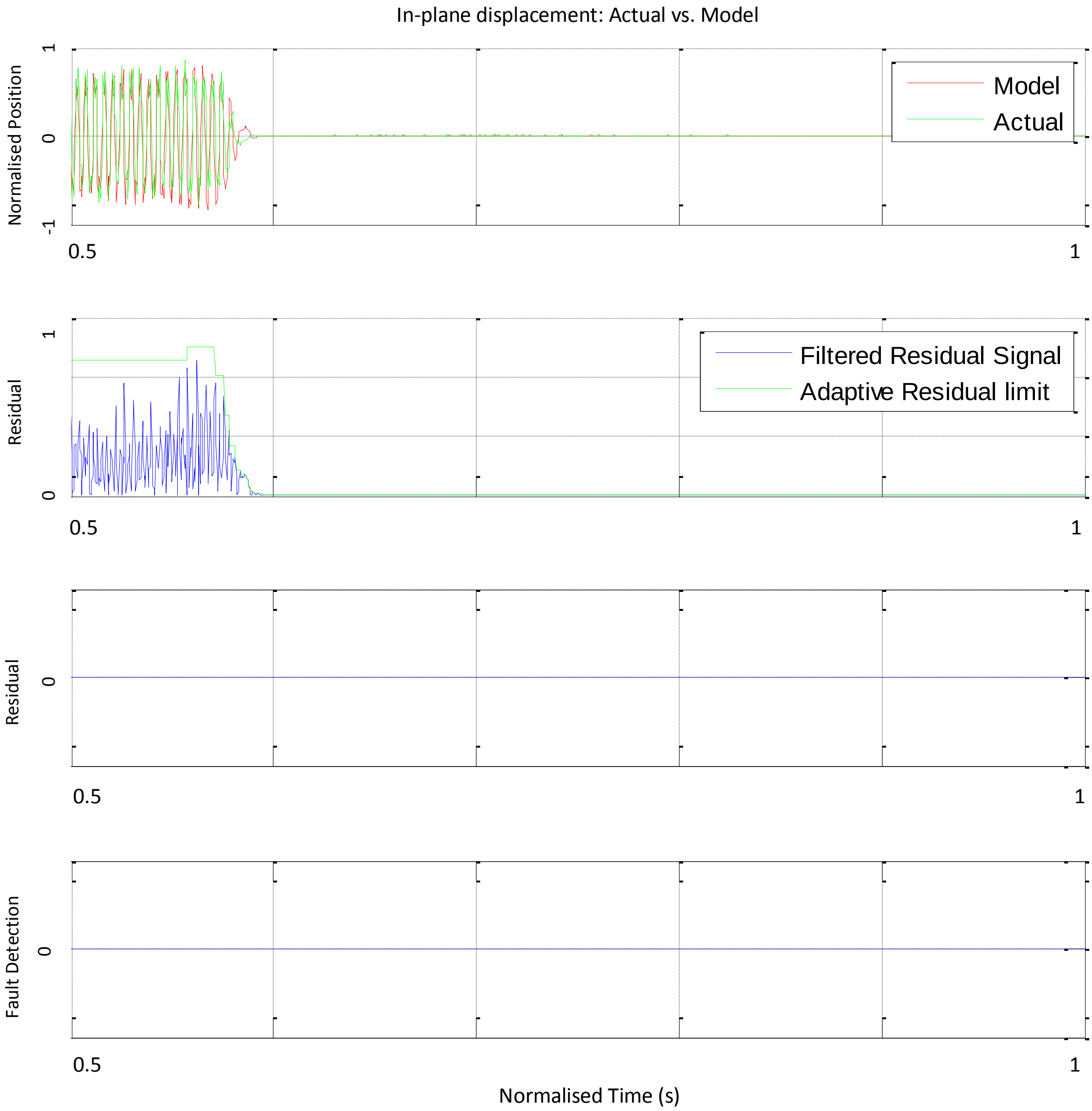


Figure 63 - Fault detection with the residual generation method (fault free)

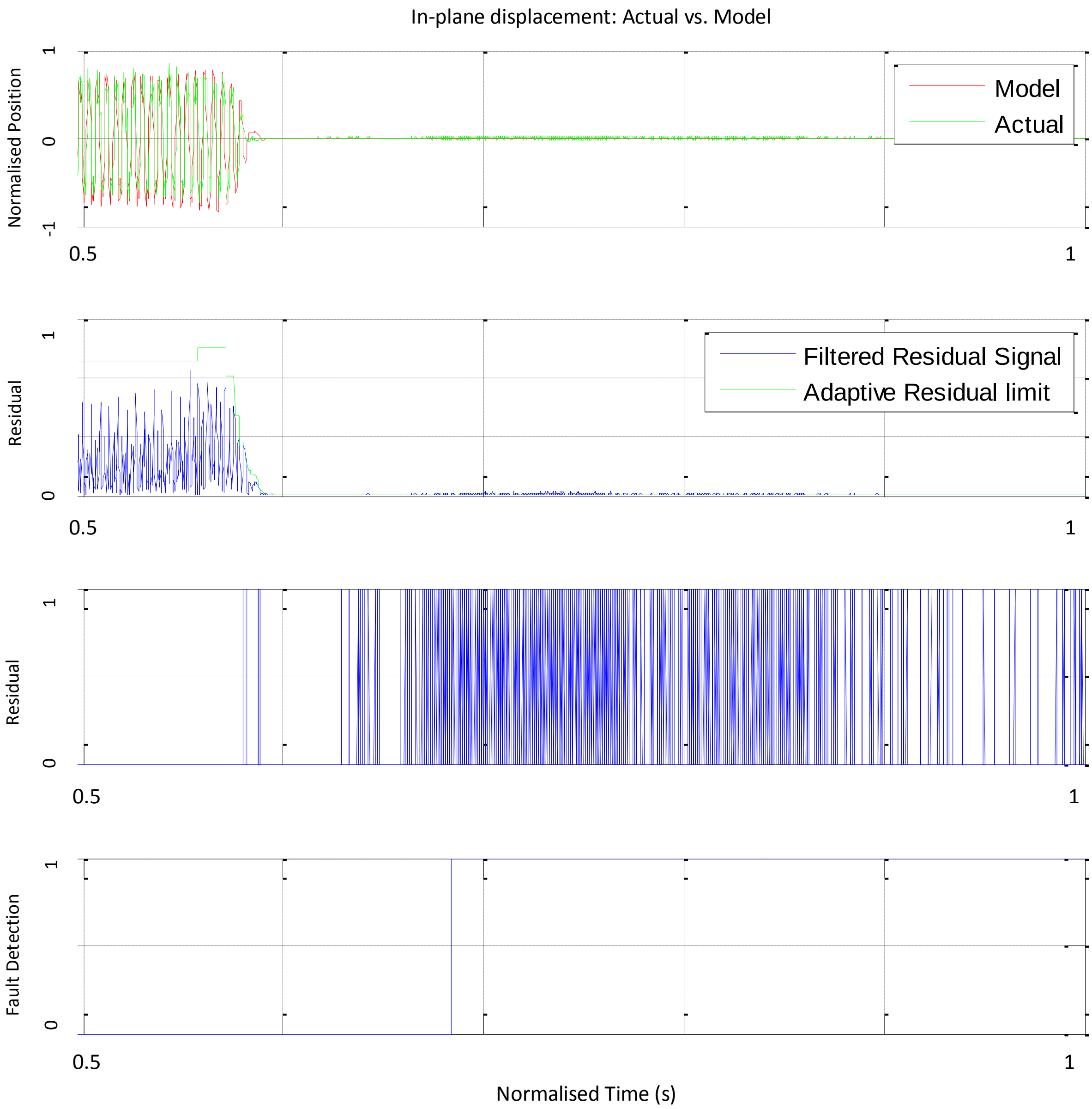


Figure 64 - Fault Detection with the residual generation method (fault)

Therefore this fault can be successfully detected and the operator/maintenance engineers notified immediately. A notification of "Valve Instabilities" would be displayed post fault occurrence. The other signals which are relevant to the isolation of this fault during the fault occurrence are shown in Appendix 8 – Fault Case 2.

1

6.3.3 Fault Case 3: Position Holding Oscillation

This fault was not detected by the machine immediately, and the fault deteriorated and after the third instance the machine limits were tripped [16]. Therefore the immediate capture of this fault by the FDI model would be of great benefit. Figure 54 shows the actual fault which appeared on the in-plane displacement signal.

Simulating a non-fault weld of the same component produces figure 65. As expected the model does not indicate any faults. The first occurance of the fault (which the machine limits did not capture) can be observed in figure 66. The FDI model successfully detects the fault occurrence – thus at this first instance an output of “Check Wiring Connections” would be displayed. Figure 67 and figure 68 show the 2^{nd} and 3^{rd} occurrence respectively of the fault. Both were not captured by the machine limits, but the FDI model effectivly captures the fault on each occurrence. Figure 69 was the weld at which the machine highlighted a fault, this too has been captured by the FDI model.

Fault free simulation example:

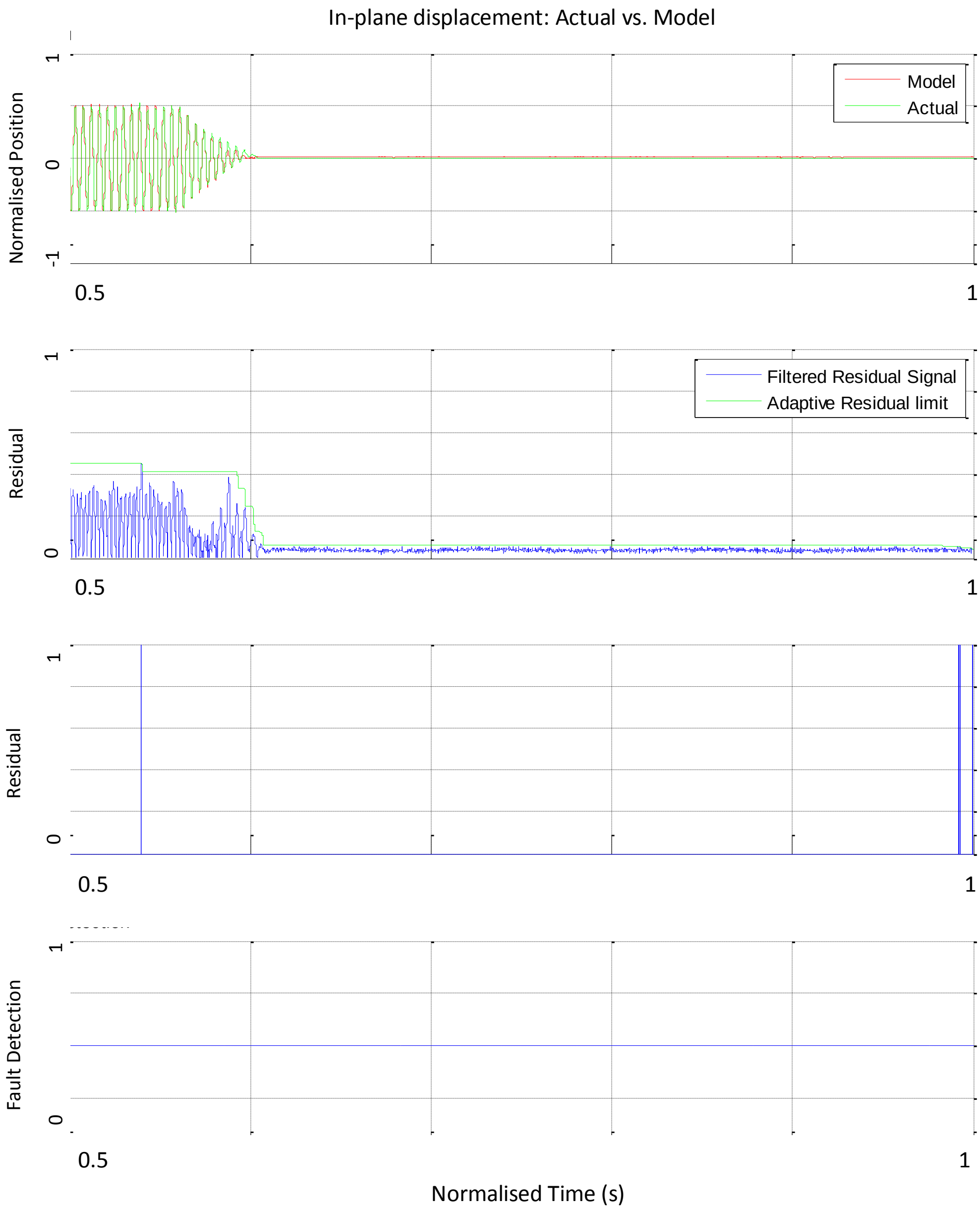


Figure 65 - Fault detection with the residual generation method (fault free)

First instance of the fault occurrence (not captured by the machine limits):

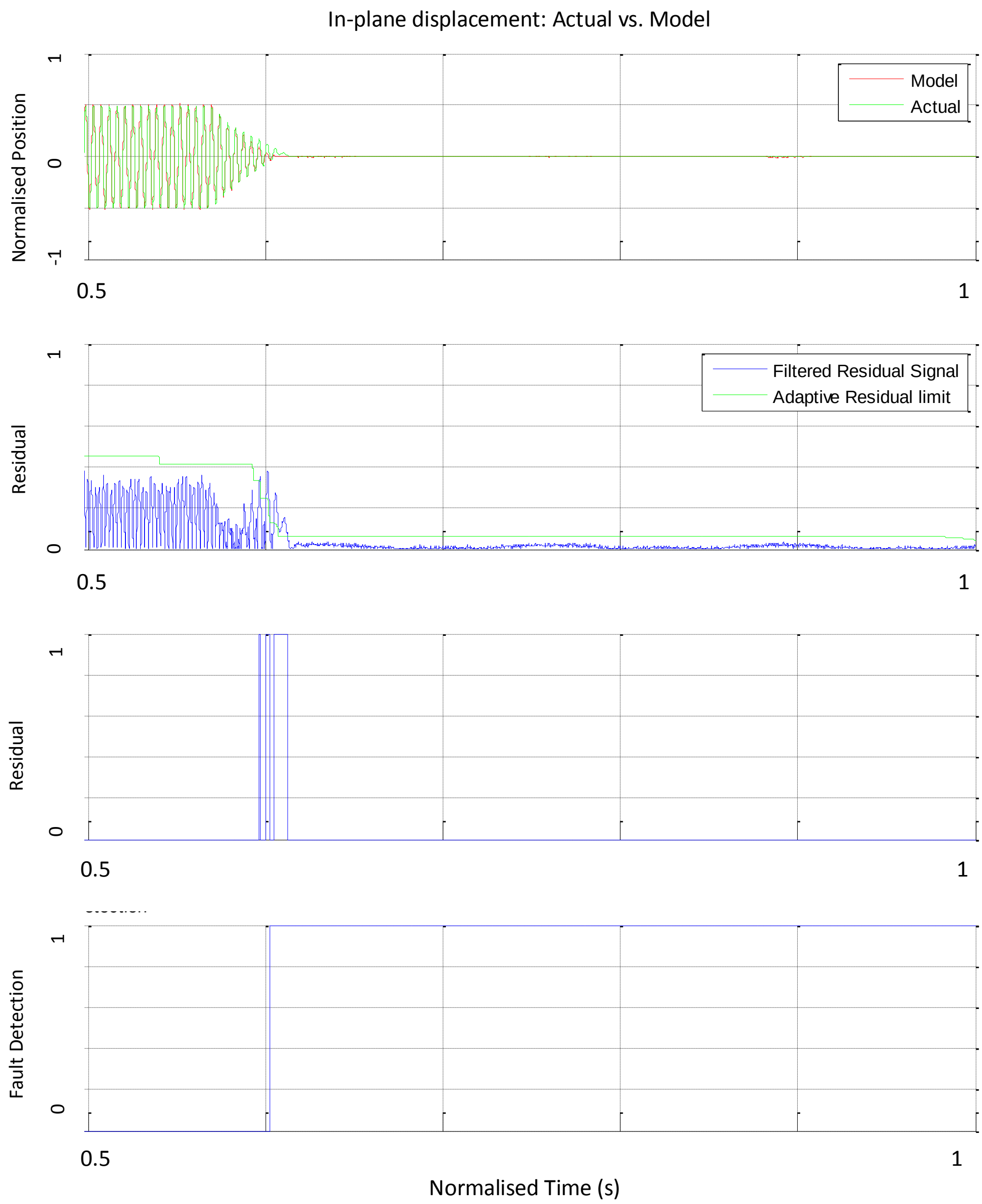


Figure 66 - Fault detection with the residual generation method (first instance)

Second instance of the fault occurrence (not captured by the machine limits):

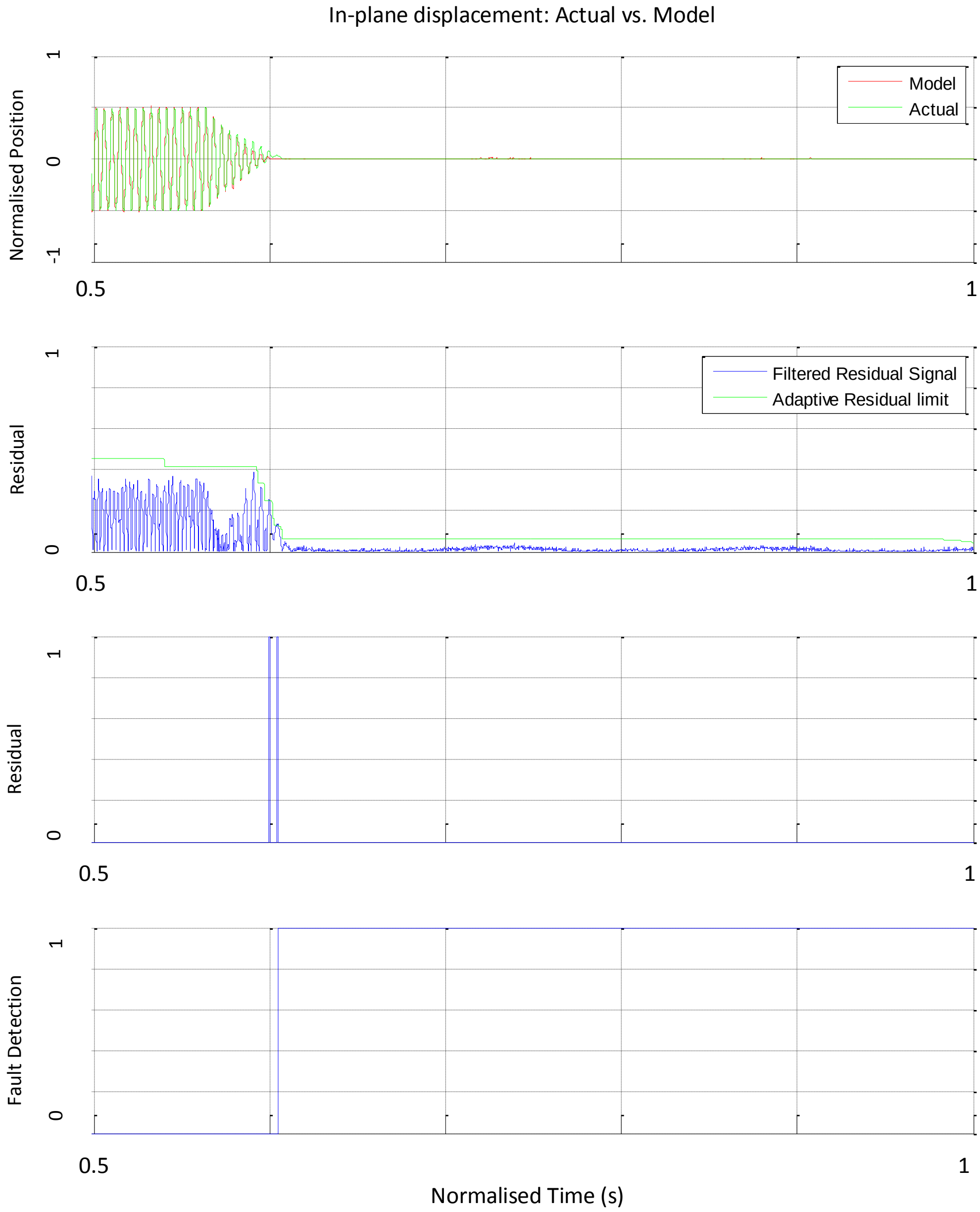


Figure 67 - Fault detection (2nd fault appearance)

Third instance of the fault occurrence (not captured by the machine limits):

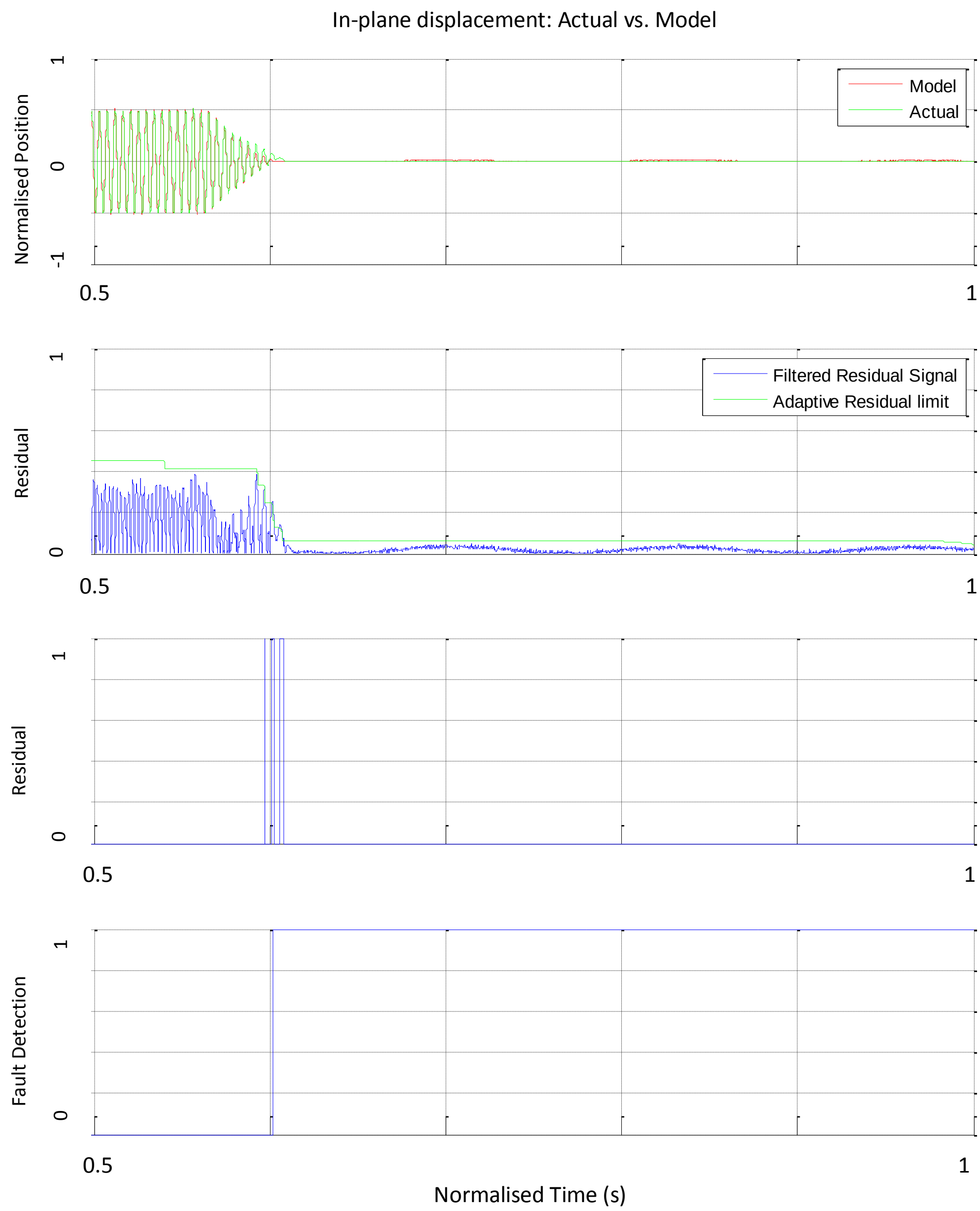


Figure 68 - Fault detection (3rd appearance)

Fourth instance of the fault occurrence (captured by the machine limits):

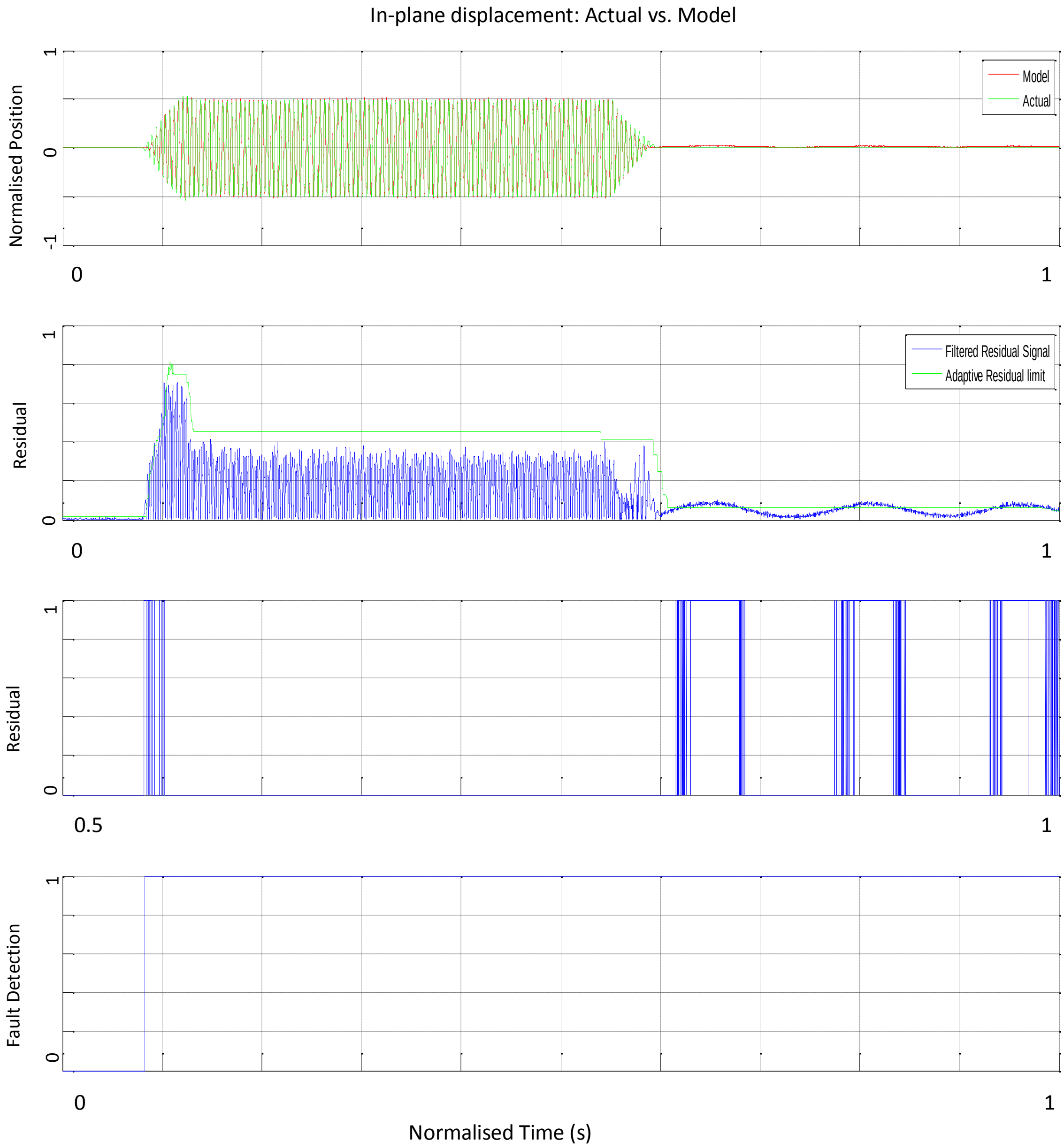


Figure 69 - Hold time Instability, Fault detection with the residual generation method (Machine limits alerted)

Therefore the model demonstrates effective capture of this fault at the first instance of its occurrence, enabling quick detection and isolation of the fault – reducing the potential for scrapping a component.

The other signals which are relevant to the isolation of this fault during the fault occurrence are shown in Appendix 9 – Fault Case 3.

6.3.4 Fault Case 4: Random Spike

The random spike fault can be seen in figure 55. As this issue was only noticed upon manual review of the data the detection of this fault by the fault diagnosis system would be of great benefit to the production process [17].

The output of fault diagnosis system simulated with the spike fault can be seen in figure 70. Due to the method of residual generation, this type of fault was not detected by the FDI model, therefore to enable detection of this fault a modified fault detection method was developed to run in parallel with the current methods.

The random spike fault was not captured by the FDI as shown in figure 70:

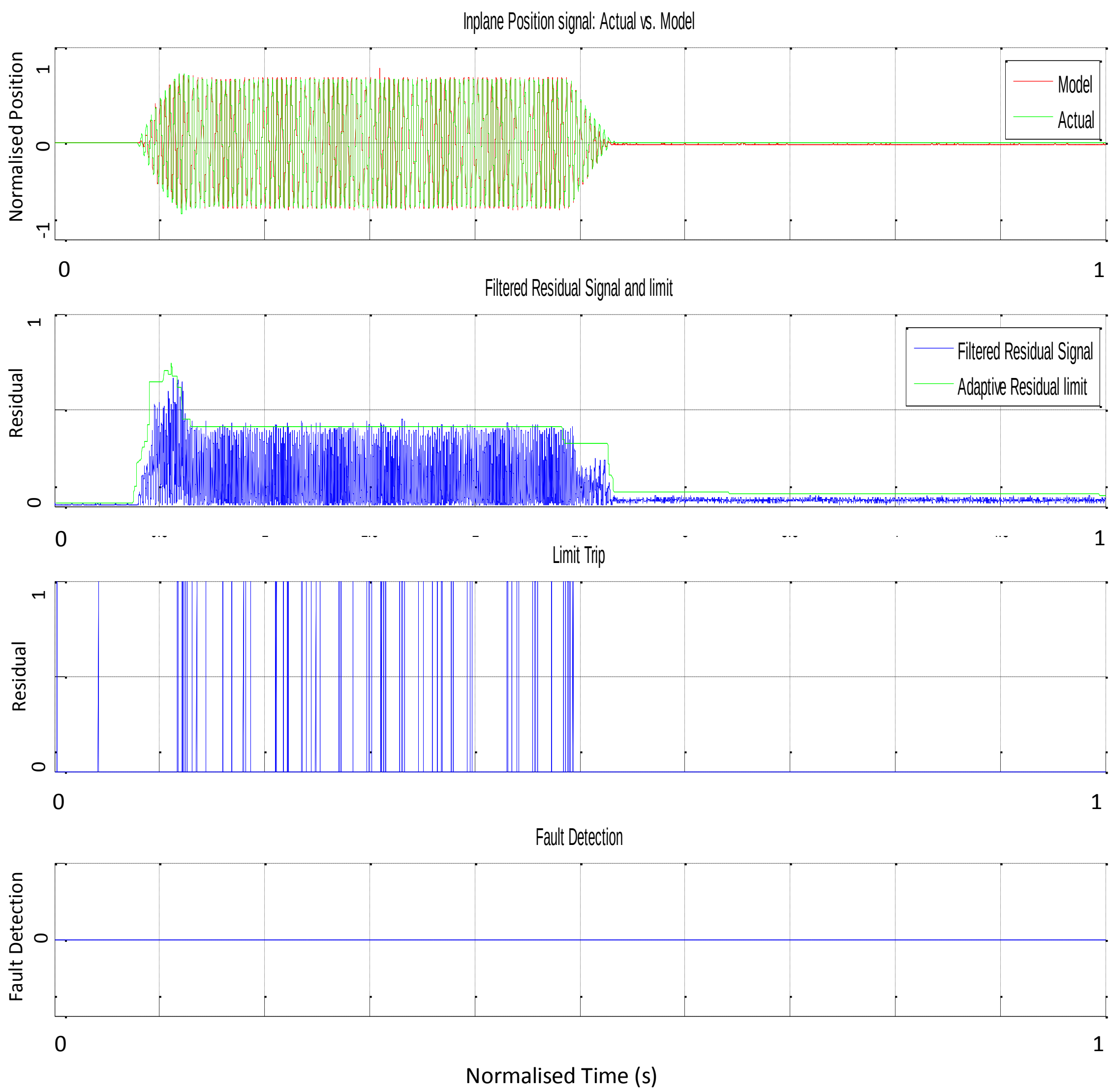


Figure 70 - Random Spikes, Fault detection investigation

This differentiated the residual before comparing with the limits. A 100 Hz analogue filter was implemented to attenuate the in-plane signals and amplify any spikes. The models implementation is shown in figure 71. An example of the fault detected is shown in figure 72.

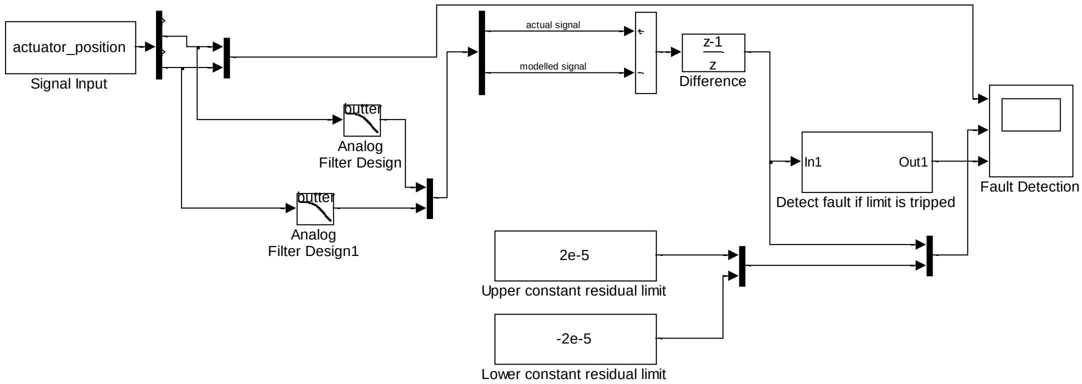


Figure 71 - Simulink model of spike fault detection

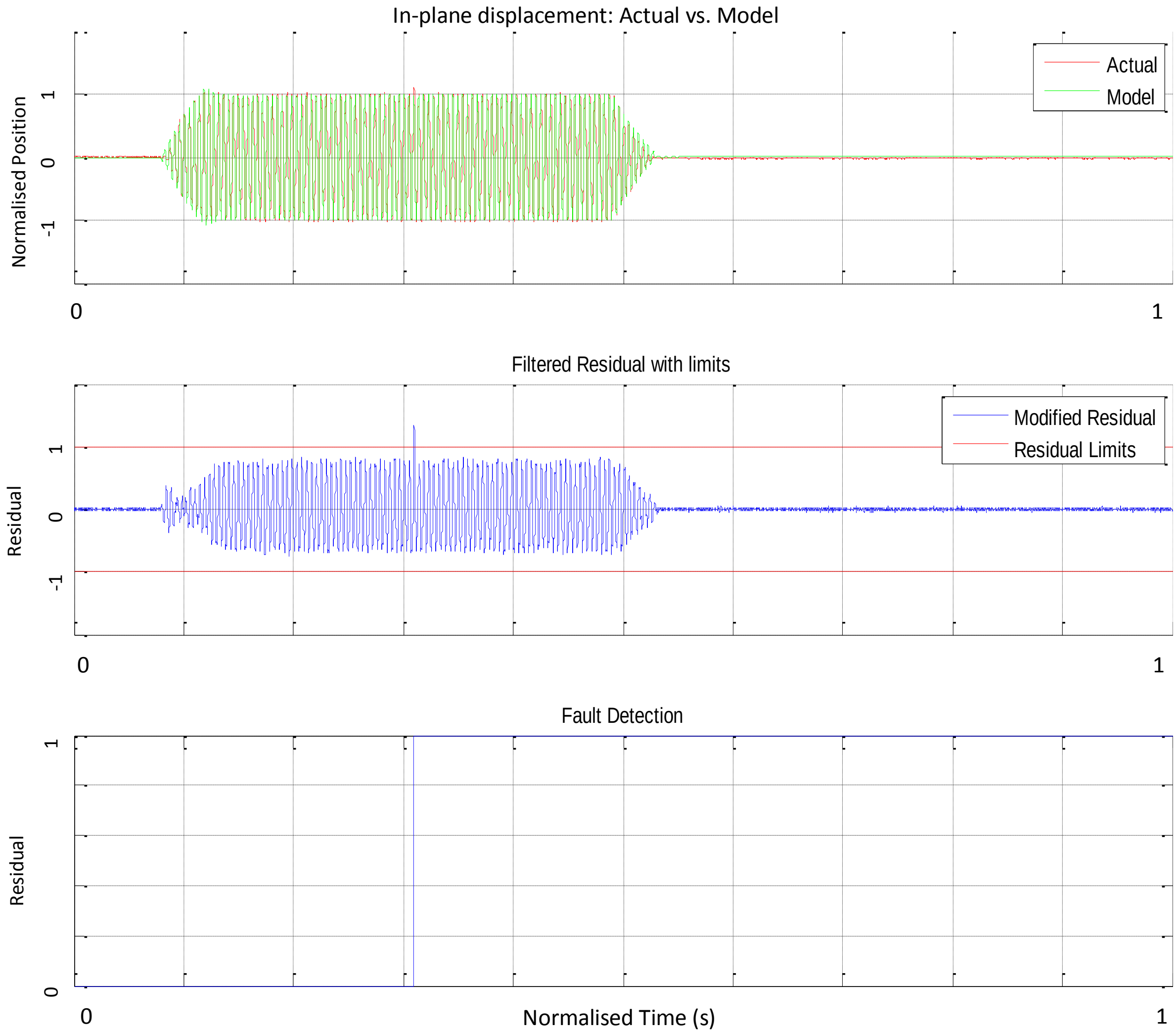


Figure 72 - Random Spikes, Fault detection investigation with a modified residual generation method

Therefore the random spike fault can now be detected. On detection of this fault the FDI model outputs “Electronics Failure”.

This section has reviewed the FDI model by simulating a number of fault and fault free cases through the model. The following section shows a model developed to enable the prediction of faults.

6.4 Fault Prediction System

The majority of faults on the LF60 are caused by the complexity of the in-plane valves due to the multiple stages utilised to provide the tangential movement. The control of the machine is very precise therefore any slight hardware or software modifications can be seen to affect the welding outputs. Previous running of the LF60 has shown a number of faults on the in-plane system which have caused instabilities during the welding process which can be detrimental to the welded part.

Associated with these faults can be machine downtime which in the past has lasted up to 3 months. The instabilities can also scrap production parts which can cost up to £250,000.

Therefore this section outlines a sub-model developed from the main model of chapter 4 which isolates the 4th Stage A and B servo valves to investigate any output measurement patterns which appear over the welding of components. This could indicate the build-up, and therefore prediction of a fault.

6.4.1 Partial Model Development

The in-plane valves on the LF60 are a dual set of 4 stage valves. A view of the 4th stages can be seen in figure 73,

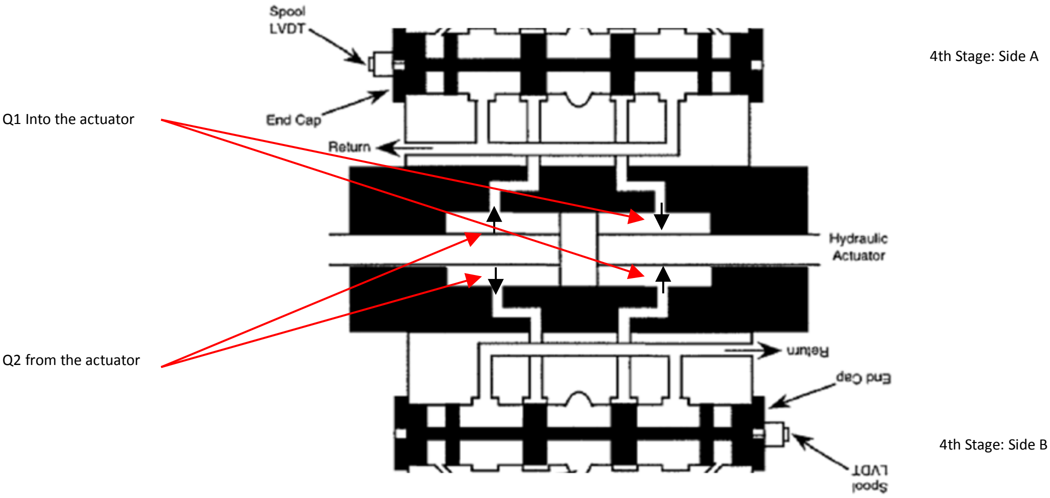


Figure 73 - 4th stage A and B servo valve arrangement example

The Simulink model of the valve 4th Stages takes into account the orifice equations using the system pressures, and spool strokes to calculate the flows which would go in and out of the actuator. A top level Simulink view can be seen in figure 74:

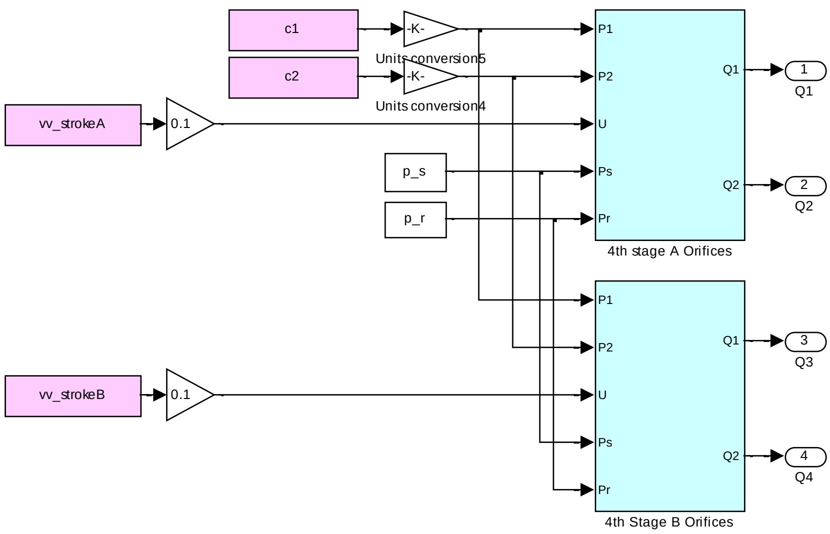


Figure 74 - Simulink Top Level Orifice model

The LF60 machine does not output internal flows as a data signal. The Simulink model can output flows, therefore the model will be used to give further insight into the in-plane system performance. Figure 75 shows a detailed view for the Orifice model.

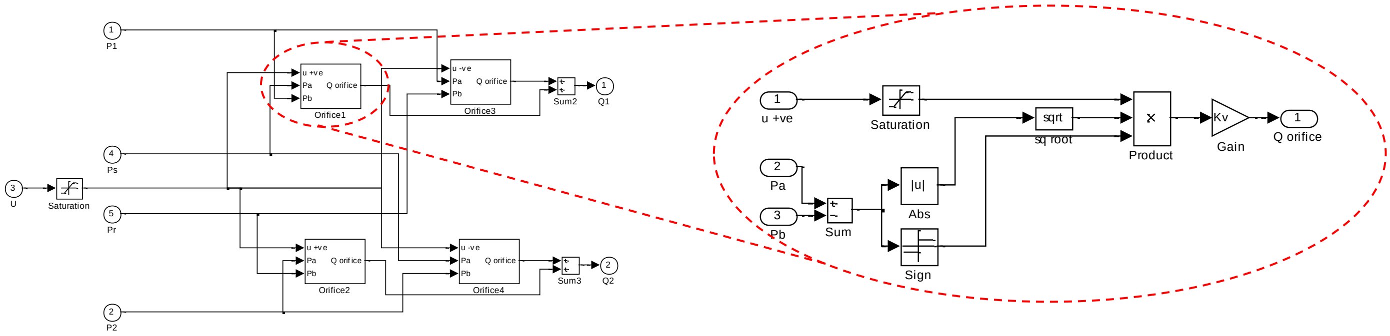


Figure 75 - Simulink Orifice Model side A/B

Details for this model including orifice equations are outlined in chapter 4 within the modelling of the 4th stage valves section 4.2.3.

A review of previously welded data identified that the differences between the 4th stage flows into and out of the actuator related to a machine instability (chapter 5.3) i.e. $Q_{1\_difference} = Q_{1B} - Q_{1A}$ had a higher value when an instability occurred as demonstrated in figure 76.

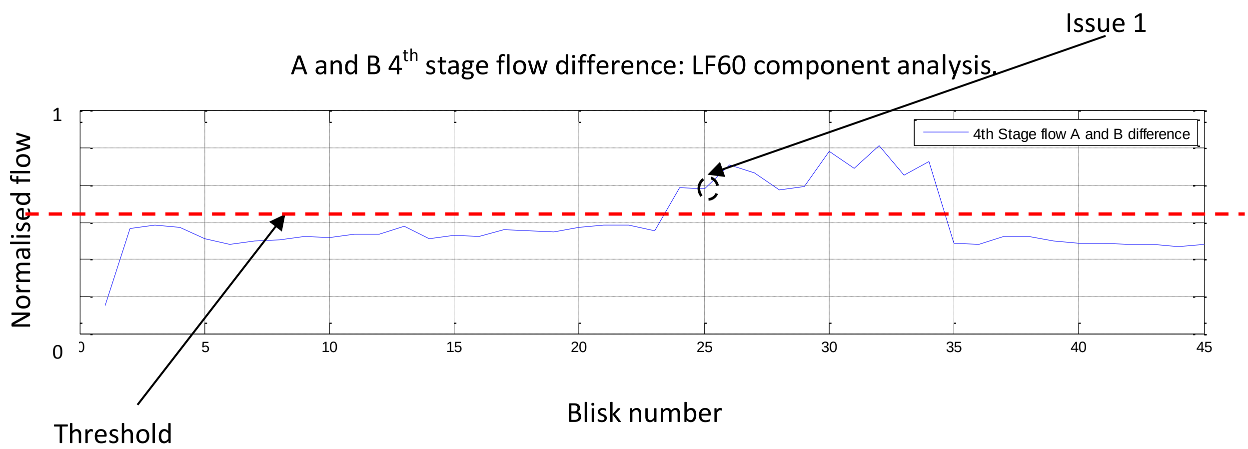


Figure 76 - 4th stage flow results

Therefore this model will be used to output the difference of the 4th stage flows as a numerical value post welding. This value will be monitored and the appropriate output signalled to the operator/maintenance informing of the increased flow difference, which therefore could lead to the increased likelihood of valve instability. Any flow outputs above the threshold would be indicated to.

6.5 Conclusion

This chapter has identified the types of faults present in hydraulics, and those occurring of the LF60 machine. Fault detection approaches have been reviewed and the most applicable one used to create a fault detection scheme for the model created in chapter 4. The FDI model has been evaluated using four different fault cases to demonstrate its capabilities, and then a fault prediction model has been reviewed. Combining all these elements has led to a FDI system which can provide fault detection, isolation and prediction of faults. A flow diagram of the whole system can be seen in figure 77.

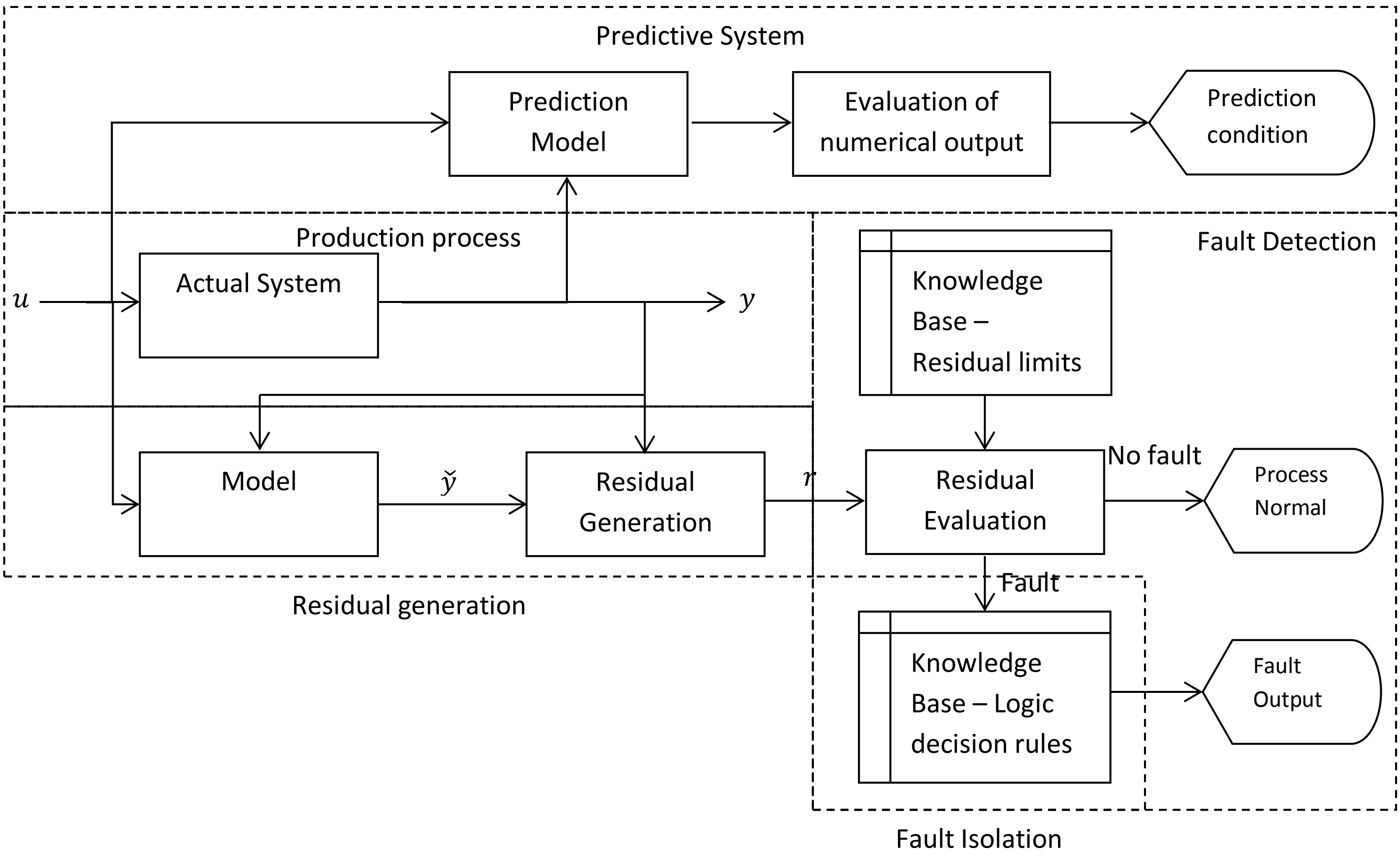


Figure 77 - Fault diagnosis system

The following research questions are applicable to this chapter,

R2: *Can the developed tool be useful in detecting and predicting faults under production conditions?*

Section 6.3 has successfully demonstrated the FDI systems ability to detect faults by simulating four different fault cases. In each of the cases the model can detect and isolate the type of fault which has occurred. Test cases 2, 3, and 4 could be detected by the model before the machines limits detected a fault, which is beneficial for a number of reasons:

- Time saving in detecting faults
- Time saving in isolating the faults and therefore fault finding
- Cost benefits in reduced likelihood of scrapping a component

Fault prediction has been successfully demonstrated by reviewing previous weld data, and the implementation of the model will allow for future indication of the increased likelihood for instabilities to occur.

Therefore this chapter has successfully answered research question 2.

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Chapter 7: Modelling – Human – Machine Understanding

7.1 Introduction

This chapter introduces a Value Improvement Model for Repetitive Processes (VIM) developed by [1] used to identify the soft system influences surrounding the FDI model implementation alongside the machine and its users. As was discussed in chapter 3 (Research Methodology), the author aims to obtain an holistic view of the research taking into account hard systems thinking (the FDI model development) and soft systems thinking (understanding the users of the model and their needs). This chapter is based on a paper accepted for publication in the conference proceedings of the Conference on Systems Engineering Research (CSER'13) [P3].

The chapter is outlined as follows: section 7.2 explores the systems thinking approaches used throughout the research along with background information and then details the VIM, its development, and applicability for use with the LFW process. Section 7.3 shows how change management is needed for the successful FDI model implementation, and the chapter is concluded in section 7.4.

7.2 Applied Systems Thinking

Chapter 2.4 reviewed the soft systems literature applicable to this research, this section will see a number of tools utilised in order to flesh out the softer systems aspects within this research project. A useful tool to get an overview of the inputs and outputs of a process defined by [2] is termed SIPOC, the acronym stand for:

- **Suppliers**: Groups or individuals providing the inputs to the process.
- **Input**: Information or materials provided to the process.
- **Process**: The steps used to carry out the process under review.
- **Output**: Product, information, or service being sent to the customer.
- **Customer**: Customers affected by the process.

Figure 78, outlines the SIPOC analysis applied to the LFW process:

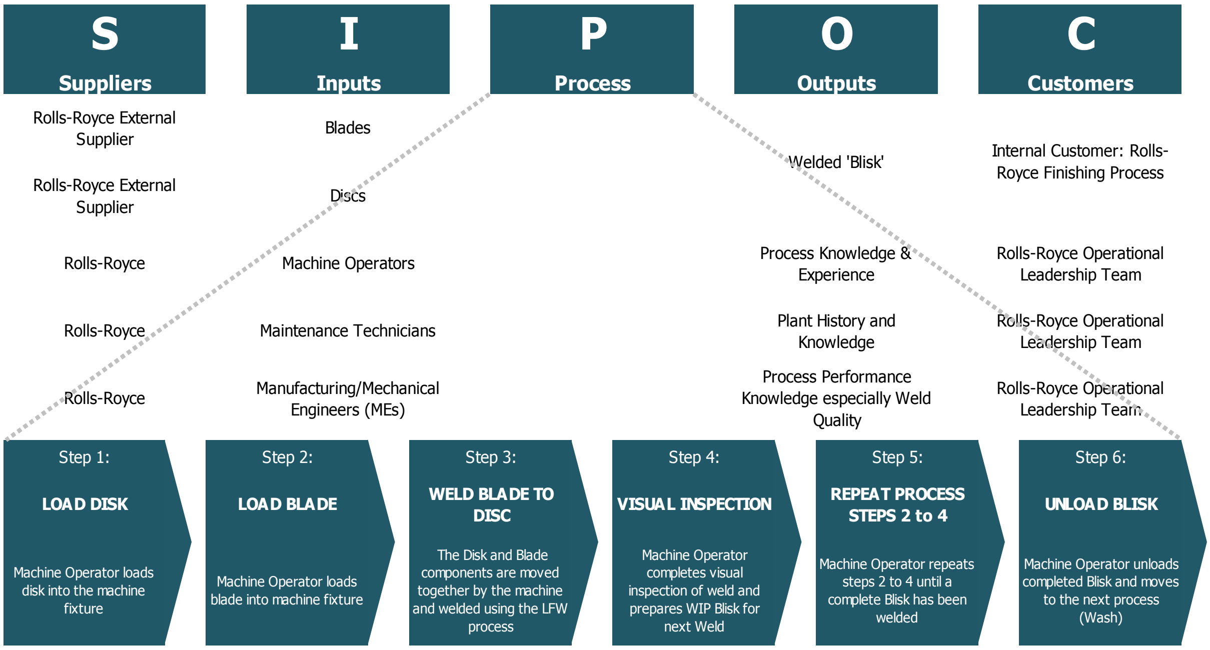

Figure 78 - SIPOC LFW Process analysis

The SIPOC model allows one to view the LFW process holistically therefore observing how and who the LFW modelling of the process affects. The LFW FDI system focuses on step 3 of the process which is the actual welding, but for this research to be implemented effectively considerations of the human inputs should be taken into account and understood. Outlined in the SIPOC diagram are the human inputs, the machine operators, mechanical engineers, and the maintenance technicians.

Once the inputs of the process have been identified to gain a detailed understanding of their insight, semi-structured interviews were performed with the different groups of people (totalling 11 interviewees: 4 ME, 3 Maintenance, and 4 Operators). These took place onsite at Rolls-Royce and consisted of 30 minute sessions to initially give a brief overview of the research purpose/progression, and then used the remaining time to ask questions surrounding the FDI model and its implementation. Interview manuscripts can be found in Appendix 10. A summary of the internal and external factors which were uncovered from the interviewing is shown in table 8.

Summary of External Influences from Stakeholder Interviews	• Welding Specifications • NuCAP US government audit • External company machine performance checks • External temperature (impacts hydraulic system) • Global economy (impacts production demand)
Summary of Internal Influences from Stakeholder Interviews	• Batch and History cards • Technical and Manufacturing Instructions • Near miss board, T cards, 7 step investigations • 5S, Gold standard • RR Quality system • Machine, Calibration and maintenance manuals • ME/materials technical documents • Maintenance FMEA, Process FMEA • Internal project work • Temperature of machine and local environment • Other machine processes on site

Table 8 - Summary of Internal and External Factors

The successful population of the linear friction welding value improvement model (*lfw*-VIM) can be achieved with use of the information gained from the FDI model development, SIPOC, and semi-structured interviews (internal and external factor analysis).

Figure 79 shows the generic VIM (*g*-VIM) developed by [1]. The VIM aims to provide an holistic framework that can be applied to any repetitive process in both service and manufacturing applications. The internal elements focus on measuring and analysing an outcome based on a requirement and feeding back improvements and updating process controls. The internal and external influencing factors encompass elements of soft systems thinking as introduced by Checkland [3].

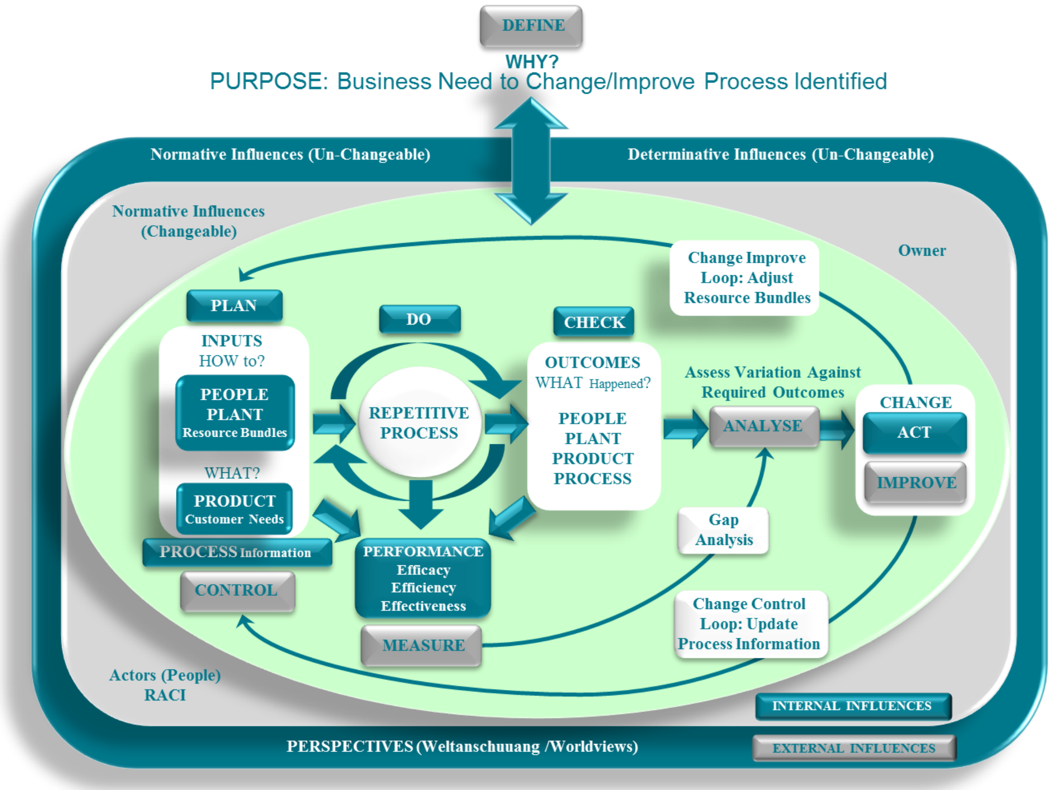

Figure 79 - Generic VIM for Repetitive Processes[1]

The individual elements of the bespoke value improvement model for linear friction welding (*lfw*-VIM) can be developed through understanding the 7Ps of the repetitive process. The *Purpose* of the *lfw*-VIM is to operationalise the FDI model of the LFW repetitive *Process;* through the interventions required by the LFW *People* to adjust the manufacturing *Plant,* the resource bundles; taking into account their individual *Perspectives;* to manufacture the Blisk *Product*; to the required *Performance* standards. Understanding the gap between the actual and measured outputs of the process, any differences would trigger a requirement to change. At the change improve point a manual intervention must be made, clearly showing the critical overlap between the hard systems FDI model, and the soft systems human control of the process. If the intervention is not made when the FDI model shows a requirement, then the process will not achieve the required output. However, the decision to make the change as requested by the FDI model is dependent on many influencing factors which the must be understood.

To develop an understanding of the influencing factors, the CATWOE tool [4] can be used to understand who/what is the Customer, Actor, Transformation process, Weltnanschuuang (Worldview), Owner and Environmental constraints of the LFW process. The *Customer* of the LFW process is the next step in the Blisk manufacturing process, the Blisk finishing process; the *Actors* involved in the process include the machine operators, maintainers, manufacturing/mechanical engineers and plant leadership; the *Transformation* of 'needs for' into 'needs met' is the LFW process itself converting a blade and disk into a Blisk; the Weltanschuuang is the different perspectives of the actors engaged in the transformation process; the *Owner* is the Plant Leader with the power to change the LFW process; the *Environmental* constraints are the internal influencing factors which can be normative and socially constructed internally at Rolls-Royce, whereas the external influencing factors can be both normative and socially constructed externally to Rolls-Royce and Determinative and independent of the LFW totally, but still influence it.

Using knowledge from the SIPOC, and semi-structure interview responses, the generic VIM presented in figure 79 has been adapted for the LFW process and the FDI system by the author as shown in figure 80.

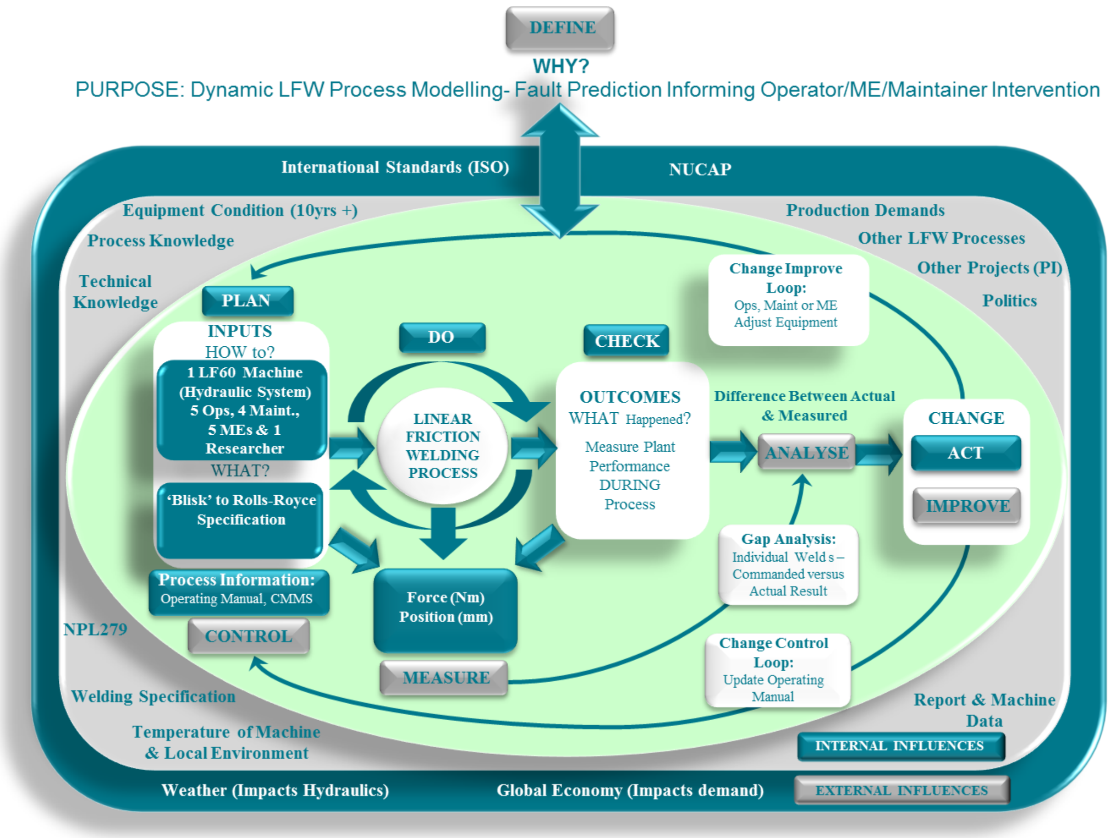

Figure 80 - LFW VIM

The *lfw*-VIM can be used to understand the gap between the actual and modelled outputs of the process, these comparisons can trigger a change requirement. At the change improve point a manual intervention must be made, clearly showing the critical overlap between the hard systems FDI model, and the soft systems human control of the process. If the intervention is not made when the FDI model shows a requirement, then the process will not achieve the required output. However, the decision to make the change as requested by the FDI model is dependent on many challenges which the must be understood.

Section 7.3 uses the LFW VIM analysis to understand implementation challenges and then shows how change management can be used to aid successful implementation of the FID model with the process and users.

7.3 LFW FDI Implementation Challenges

The successful implementation of the FDI model through the *lfw*-VIM presented in figure 80 is dependent on understanding how the trigger to intervene with the process impacts the individuals who have functional responsibility for the process. For example the operator will receive a notification from the model from which they will notify mechanical engineers of its occurrence. Then depending on the fault type as shown in Table 9 either the operators and maintenance, or maintenance and mechanical engineers, will work together to rectify or prevent the fault.

Examined Fault Case	**Model Output**	**Machine Operator Action**	**Operator**	**Maintenance**	**Mechanical Engineer**
Fault 1: Start-up oscillation	Check HSM	Notify Mechanical Engineer to confirm presence of a fault	Work together to restore normal machine operation		
Fault 2: Holding force oscillation	Valve instabilities	Notify Mechanical Engineer to confirm presence of a fault	Work together to restore normal machine operation		
Fault 3: Low frequency holding oscillation	Electronics failure	Notify Mechanical Engineer to confirm presence of a fault	Work together to restore normal machine operation		
Fault 4: Random spike during oscillation phase	Check wiring connections	Notify Mechanical Engineer to confirm presence of a fault	Work together to restore normal machine operation		
Prediction of fault	Out of limit notification	Notify Mechanical Engineer to confirm presence of a fault		Work together to mitigate the high probability of a fault occurrence	

Table 9 - Model Outputs and Actor Actions

Therefore for the appropriate action to be taken and the model outputs effectively responded to by each of the users, trust and respect for the FDI system and its developer had to be gained. This was achieved over time as the researcher was embedded in the organisation for a number of years, while working alongside the actors. The implementation of practices to help speed up maintenance routines has gained respect, and the knowledge applied for the prompt solution to machine fault resolution has gained a level of trust with the actors. This is a critical element in the implementation of the FDI model and was mentioned multiple times in the semi-structured interviews.

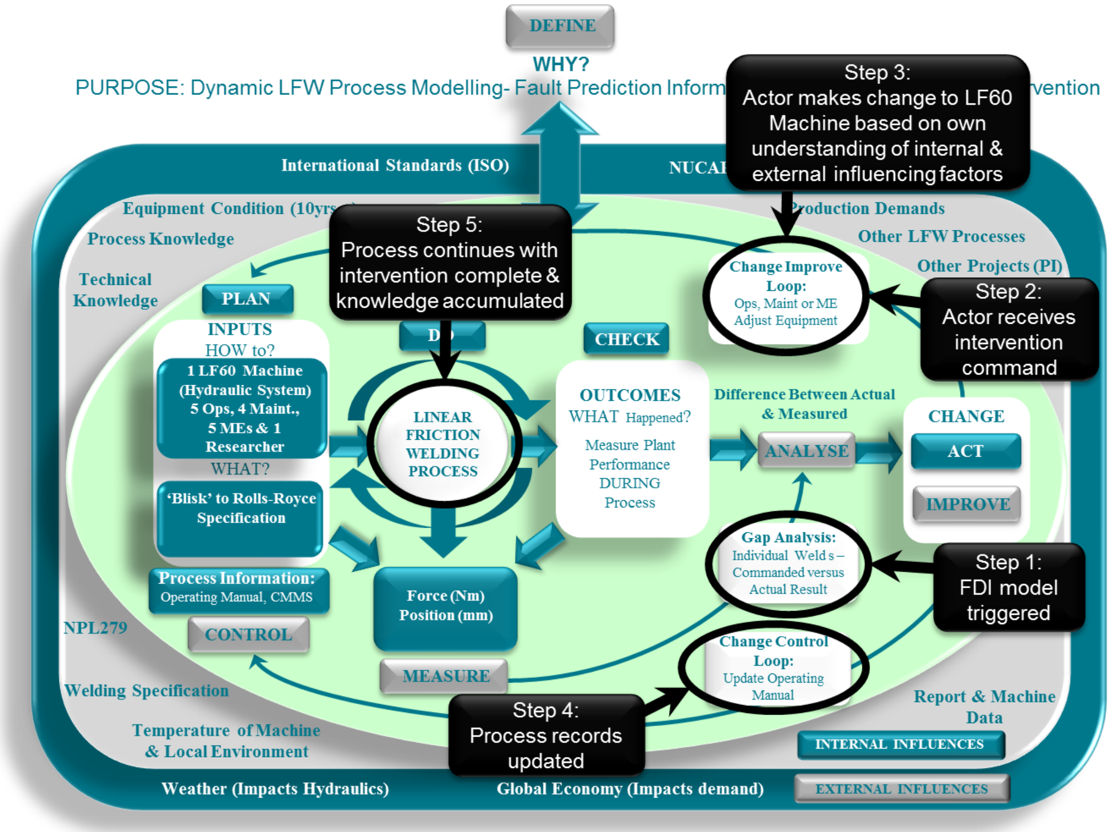

Figure 81 - *lfw*-VIM implementation: Actor intervention

Showing the links between the influencing factors, figure 81 illustrates the steps leading up to, and the specific point in the *lfw*-VIM where the actors must make a manual intervention to the process. This is a critical step in the process as the operator has to trust the data provided by the FDI model and stop what may seem like an error free process. The actors also have to take into account the many other influencing factors as part of their decision to intervene. For example, the machine operator knows the physical equipment is over 10 years old; is this the reason for the change in the process performance as the plant condition deteriorates and impacts the repetitive process? Other questions the operator may ask themselves, based on influencing factors include:

1. Has this fault occurred before and the intervention made successful?
2. Is the temperature and environment of the facility impacting the process performance?
3. Do they (I) have enough experience and knowledge of the process to make the intervention and correct the process?
4. Is there pressure from the leadership team to fulfil customer demand in the short-term?
5. Is another measures of process performance (such as SPC) indicating there is not a problem?
6. Are there enough resources on site/available to support the intervention should it fail?

Theses influencing factors can be described in a force field analysis, to outline the forces driving or restraining the change implementation [5] figure 82 shows the force field analysis of the FDI model adoption.

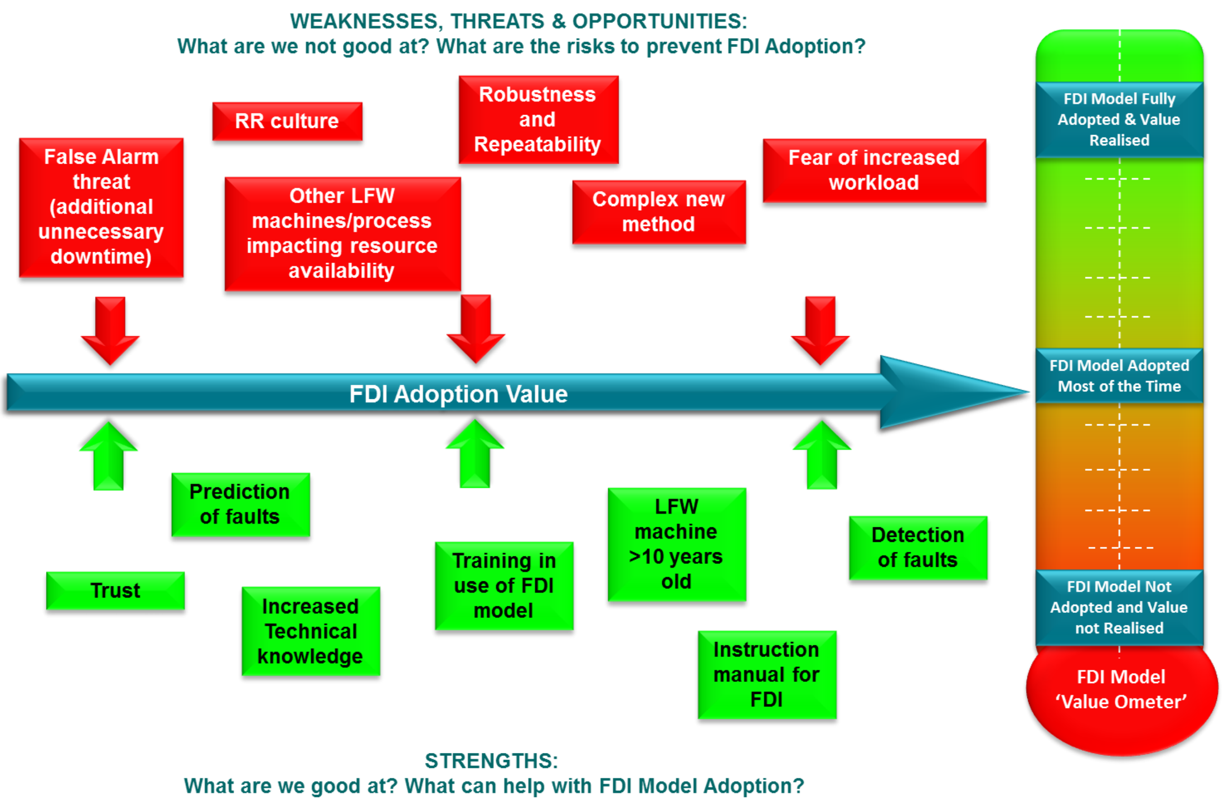

Figure 82 - Force Field analysis

With the understanding of the restraining forces to model implementation these can be discussed and mitigated against with the users of the system to enable successful FDI model implementation with the process.

7.4 Conclusion

Though this holistic modelling, it has been possible to identify the critical elements to be taken into account when translating this -people, plant, product and process based- understanding into meaningful and achievable implementation.

This chapter has shown how a hard systems model of a hydraulic system can be understood from multiple perspectives using a value improvement model to understand the soft system influencing factors. More specifically, an *lfw*-VIM has been introduced showing how the critical links between the hard systems analytical FDI model of a complex electrohydraulic system is dependent on the human intervention required to utilise the model.

The value improvement model has been successfully applied to the Linear Friction Welding process and the developed FDI system with the aims of answering the following research question:

R3: *What considerations are needed for effective tool deployment with the machine and human interactions?*

This chapter has outlined FDI and human interactions and showed where considerations need to be made for its successful implementation. One of the most important features of the model needs to be its reliability, from the semi-structured interviews comments were made on trusting the model. Given that the author has been embedded in the company and provided assistance with a number of previous machine issues, technical authority has been gained therefore there is a high likelihood that the FDI actions will be acted upon. Combined with the analysis of the model sensitivity to faults (chapter 6) the model can be trusted to effectively identify fault situations which have previously occurred.

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Chapter 8: Conclusion

8.1 Introduction

This chapter will revisit the research hypothesis and questions to draw conclusions to the thesis and then outline contributions to the body of knowledge.

The research hypothesis posed in chapter 1 was:

Systems thinking can be applied to a complex Linear Friction Welding machine; in order to create an analytical model of its behaviour enabling the development of a fault detection and prediction tool alongside understanding the human–machine interactions to aid effective tool deployment at Rolls-Royce.

This thesis attempts to answer the hypothesis by initially introducing the research in chapter 1 giving background and further information on the investigation. Chapter 2 reviewed the literature on hard and soft systems thinking outlining an understanding of the techniques, theories and practices used within. The methodologies used to answer the research was both quantitative and qualitative enabling an analytical model to be developed while understanding the human aspects of the research as summarised in chapter 3. The following four chapters were used to answer the three research questions. A reminder of the research questions and a discussion of how the thesis demonstrates the answers are presented below.

R1: *Can an analytical model be developed to accurately represent a complex physical electro-hydraulic system?*

Research question 1 aims to find out initially if a model of the machine's key systems can be developed, and if so does the model represent the behaviour of the system accurately? This thesis demonstrates the hydraulic system modelling in chapter 4, where the complex multiple servovalve in-plane system and its dynamics are modelled. The simulation and validation is demonstrated in chapter 5, using a variety of statistical techniques to show how well the model matches the actual systems operation. Validating the model indicated that some signals were better represented then others, for example the in-plane displacement feedback signal only had 7% Normalised Root Mean Squared Error (NRMSE), whereas the in-plane force signal had 41% NRMSE. Given the main aim of the research was to create a fault detection and prediction tool, the following chapter (6) which assesses the model with a number of actual fault cases can also be used to determine if the modelling is accurate/suitable for purpose.

R2: *Can the developed tool be useful in detecting and predicting faults under production conditions?*

The second research question is closely linked with the first, in that if the developed model can detect and predict faults then it would be deemed accurate enough for its purpose. Chapter 6 aimed to demonstrate this by simulating the model with actual machine fault and fault free data and to determine if the modelling can be used alongside production to detect these faults, and predict when a fault could occur. Four case studies reviewing different faults were identified, and it was shown that the model under the different conditions was sensitive enough to detect each of the faults. Due to the high NRMSE of some signals full scale fault prediction was not achieved but in developing a sub model of the in-plane system (see chapter 5 section 5.3) gradual deterioration before a significant failure occurrence could be monitored. Therefore indicating when the machine state could be in a higher probability of a fault occurrence.

Research question 1 and 2 are demonstrated diagrammatically in figure 83, showing an overview of how the modelling work fits together with the production process.

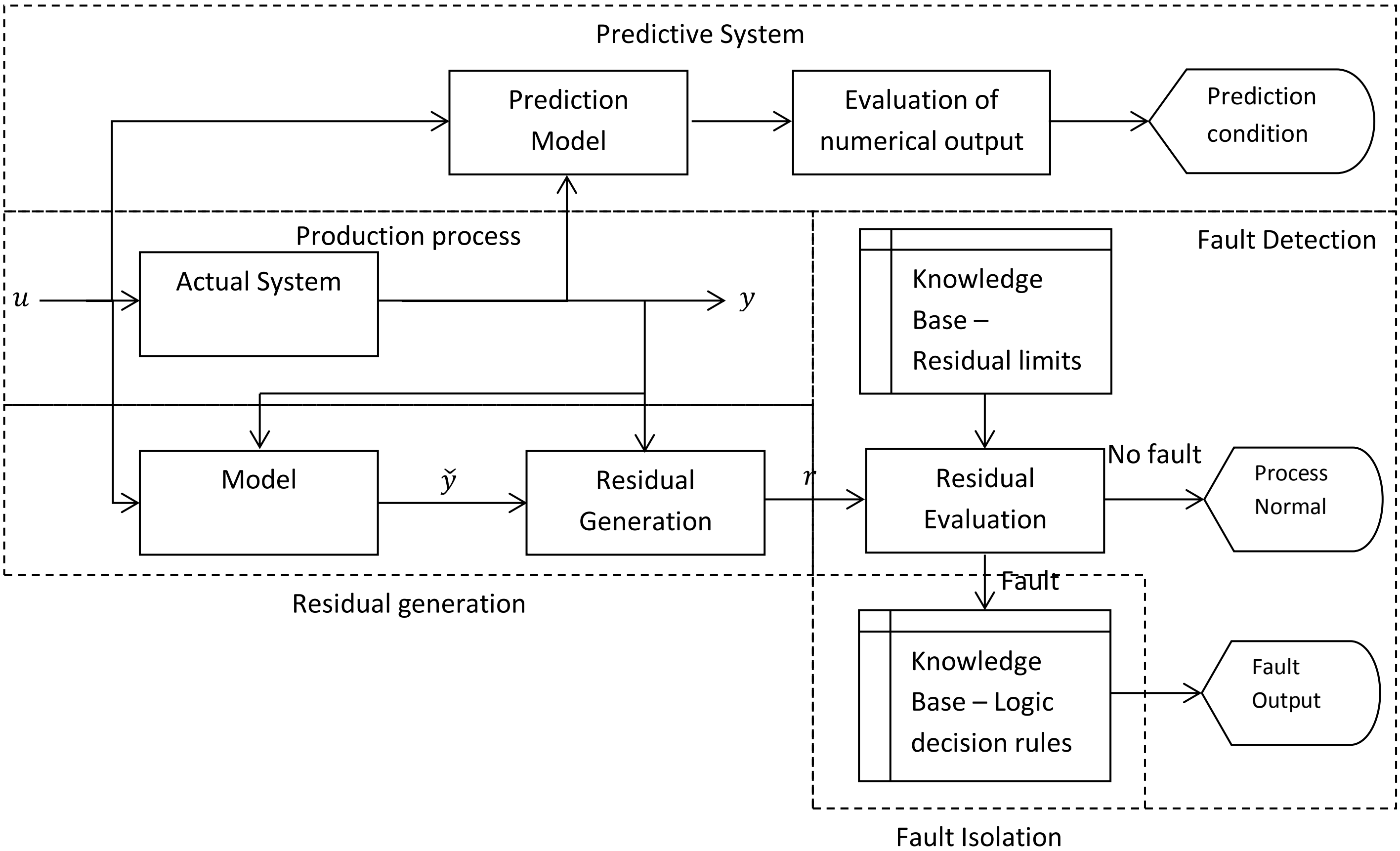

Figure 83 - Fault detection and prediction system for the LFW process

R3: *What considerations are needed for effective tool deployment with the machine and human interactions?*

The development of a suitable model which can detect and predict faults for an industrial production machine is useless if the model is not known, understood, and/or acted upon. Chapter 7 utilised a Value Improvement Model, in a novel approach to understand the human (soft systems) elements, surrounding the production process and the model to enable effective deployment of the tool. Interviews with the users of the production machine were held to improve awareness of the models' capability and purpose, and gain an insight into any operational challenges which could arise. The main findings of this chapter were the highlighting of possible threats to model implementation, which in turn were discussed with the users and mitigated wherever possible to enable successful model implementation as shown in figure 84.

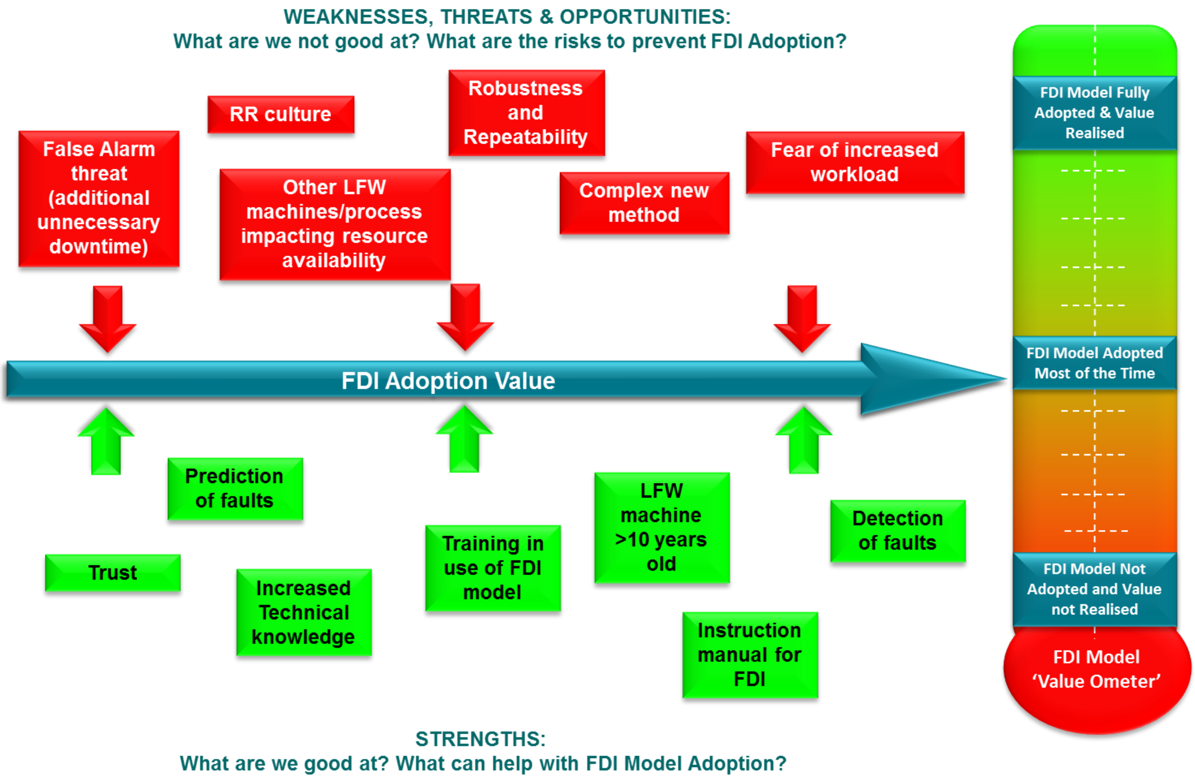

Figure 84 - Model adoption showing weaknesses and strengths from semi structured interviewing process

8.2 Contributions

The main contributions to the body of knowledge from this thesis are:

- The modelling of a dynamic actuation system for the LFW machine.
- The development of fault detection methods for a LFW model.
- The development of fault prediction methods for a LFW model.
- A Novel approach in understand human-machine interaction of an industrial repetitive process

8.3 Future Work

The main areas for consideration are:

1. Full model development of the whole of the LFW hydraulics system, including all mechanical axes, controllers, servovalves, and actuators.
2. Fault detection and prediction capabilities implemented on a full scale model of the LFW machine, using similar principles defined within this thesis.
3. Modelling to give the capabilities for predicting other failures on the LFW machine.
4. Modelling of other complex machinery for fault detection and prediction purposes using the principles defined within this research.

Appendix 1 – Empirical Function

This Appendix outlines the empirical function developed in Matlab used to calculate the in-plane force at the weld as described in chapter 4, section 4.2.5.1.

```
function[force] = weldfric(xdot, x, max_amp, Fz)

% function to model the weld friction characteristic initially
developed by
% Chris Lamming and Andrew Plummer, October 2007. Utilised by Darren
% Williams with Model modification, August 2008.

%minimum velocity seen to produce the maximum friction coefficient
at the
%initial and end of the cycle.
v0 = 0.05;

%Estimate of the maximum 'friction coefficient' seen in the weld
data
mu_max = 0.55;

% Algorithm to determine the current displacement amplitude, based
on the
% displacement signal - assuming we can store values somewhere from
one
% step to the next
global x_old;
global climbing;
global x_max;

x_new = x;

if(x_new >= (x_old + 0.5e-4))
    if(climbing == false)
        climbing = true;
    end
    x_old = x_new;
elseif(x_new < (x_old - 0.5e-4))
    if(climbing == true)
        x_max = x_old;
        climbing = false;
    end
    x_old = x_new;
end

%Ramp up the weld model as it appears in the weld data from RR -
this is
%the value of velocity where the maximum friction coefficient is
seen.
v1 = v0 + (x_max/max_amp)*0.37;

%Derive the initial slope, assumes that the line passes through the
origin,
```

```
%which is a simplification since the observed data shows hysteresis
m1 = mu_max/v1;

%Take the falling slope as a constant
m2 = -1.5;

if xdot < -v1
    mu = (m2 - m1)*v1 + m2*xdot;
    if(mu > -0.3)
        mu = -0.3;
    end %if
elseif (xdot >= -v1) && (xdot <= v1)
    mu = m1*xdot;
else
    mu = (m1 - m2)*v1 + m2*xdot;
    if (mu < 0.3)
        mu = 0.3;
    end %if
end %if

force = mu*Fz; %[in units of force received]
```

Appendix 2 – Model Simulation and NRMSE Calculation

This appendix reviews the normalised root mean square error (NRMSE) calculation and shows an example model simulation.

The steps needed to calculate the NRMSE are outlined as follows:

1. Execute the in-plane simulation model to save all the relevant variables to the Matlab workspace
2. Execute the NRMSE simulation model to calculate the NRMSE values for each of the signals, comparing the models output to the actual systems output.

An example of the NRMSE model simulated with test data is shown in figure 85.

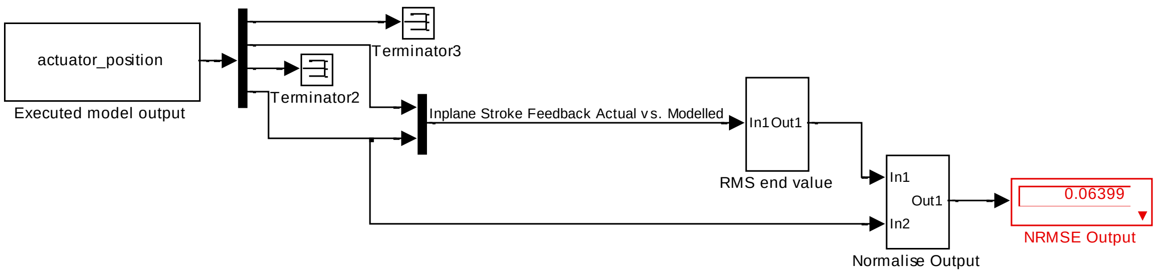

Figure 85 - NRMSE model simulation

Appendix 3 – Matlab Files: Amplitude Ratio, Phase Difference, and Frequency Check

This Appendix outlines the Matlab files used to calculate the amplitude ratio, phase difference and frequency check.

1. Amplitude Ratio and Phase Difference

```
function []=AR_and_PD(actual,model)
% This function calculates the Amplitude Ratio and Phase Difference
for two
% signals of the same length
%
% Darren Williams - March/2009

x=actual;    %Inputs the actual signal into variable x
y=model;     %Inputs the model signal into variable y

x = x - mean(x);     %Removes the bias of the signals
y = y - mean(y);

X=fft(x);    %Calculates the discrete fast Fourier transform of the
signals
Y=fft(y);

%From the FFT, find the maximum peak which corresponds to the
magnitude at
%an index point
[mag_x idx_x] = max(abs(X));
[mag_y idx_y] = max(abs(Y));

%From the FFT, finds the index where the max peak is - to calculate
the
%phase difference at the maximum point - PD
px = rad2deg(angle(X(idx_x)));
py = rad2deg(angle(Y(idx_y)));
Phase_Difference = py - px      %PD- Not suppressed so this gets
output when the function is executed

%Output Amplitude/Input Amplitude = amplitude ratio (AR)
Amplitude_Ratio = mag_y/mag_x  %AR- Not suppressed so this gets
output when the function is executed
```

2. Frequency Check

```
function []=freq(actual,model)
% This function calculates the frequency of two signals, and thus
can detect
% frequency differences
%
% Darren Williams - March/2009

x=actual;
y=model
;
% Sampling frequency
Fs=1028;

% Use next highest power of 2 greater than or equal to length(x) to
calculate FFT.
nfft= 2^(nextpow2(length(x)));
nffty= 2^(nextpow2(length(y)));

% Take fft, padding with zeros so that length(fftx) is equal to nfft
fftx = fft(x,nfft);
ffty = fft(y,nffty);

% Calculate the numberof unique points
NumUniquePts = ceil((nfft+1)/2);
NumUniquePtsy = ceil((nffty+1)/2);

% FFT is symmetric, throw away second half
fftx = fftx(1:NumUniquePts);
ffty = ffty(1:NumUniquePts);

% Take the magnitude of fft of x and scale the fft so that it is not
a function of % the length of x
mx = abs(fftx)/length(x);
my = abs(ffty)/length(y);

% Take the square of the magnitude of fft of x.
mx = mx.^2;
my = my.^2;

% This is an evenly spaced frequency vector with NumUniquePts
points.
f = (0:NumUniquePts-1)*Fs/nfft;
fy = 0:NumUniquePtsy-1)*Fs/nffty;
loc=find(mx == max(mx));
locy=find(my == max(my));

freqx=interp1(f,loc)    %Frequency of the actual signal, not
supressed so outputs when the function is executed
freqy=interp1(fy,locy)  %Frequency of the model signal, not
supressed so outputs when the function is executed
Delta_Freq = freqy-freqx %Frequency difference of the actual vs
modelled signal, not supressed so outputs when the function is
executed
```

Appendix 4 – Remaining Validation Results

This appendix reviews the remaining validation results from chapter 5, section 5.2.3.1.

The in-plane acceleration signal is measured on the LF60 by an accelerometer, and used in the calculation of the in-plane force signal. The in-plane acceleration comparison shows a higher NRMSE, due to the machine dynamics not being fully captured. NRMSE data is shown in figure 86, the average percentage error is 29% and the maximum is 41% on the 15th data set.

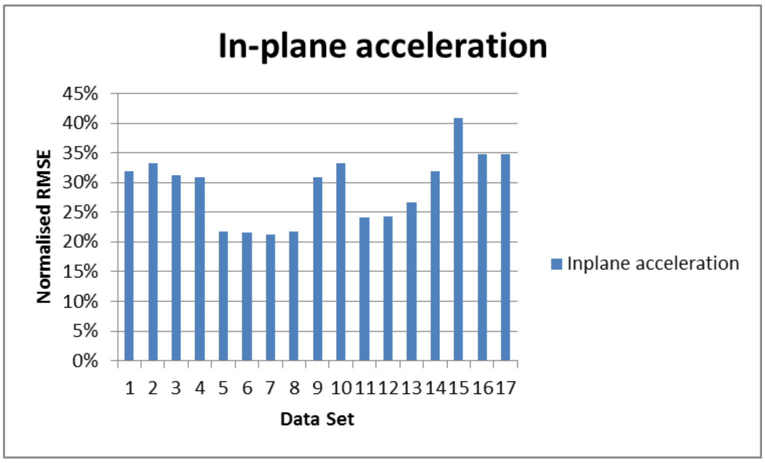

Figure 86 - In-plane Acceleration NRMSE

Time series data for the 15th data set can be seen in figure 9, zoomed in figures are shown in figure 87.

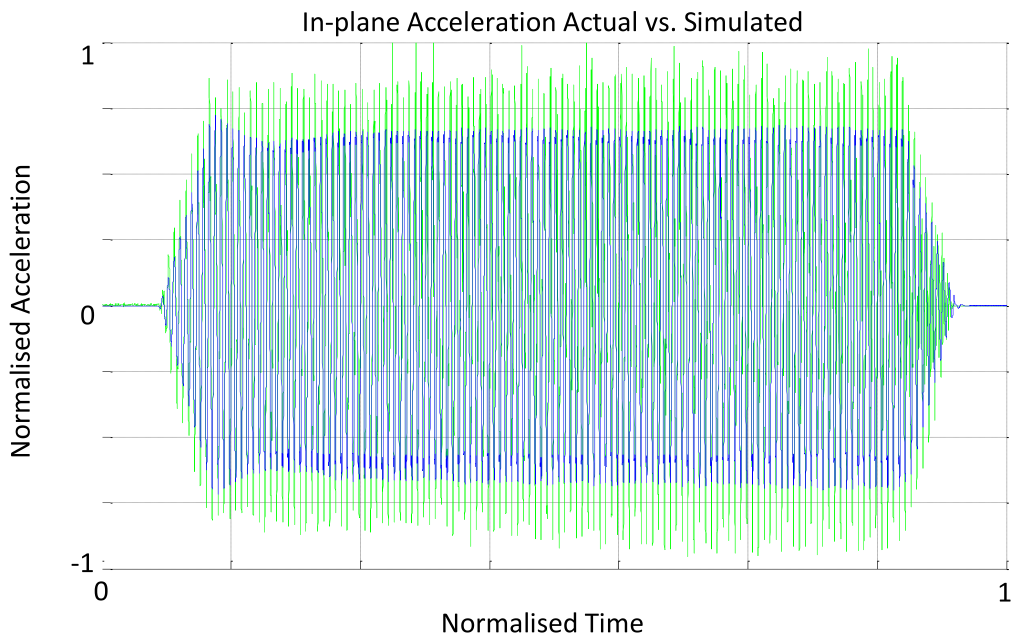

Figure 87 - In-plane Acceleration Time Series

Zoomed in timer series response for the in-plane acceleration signal data set 15:

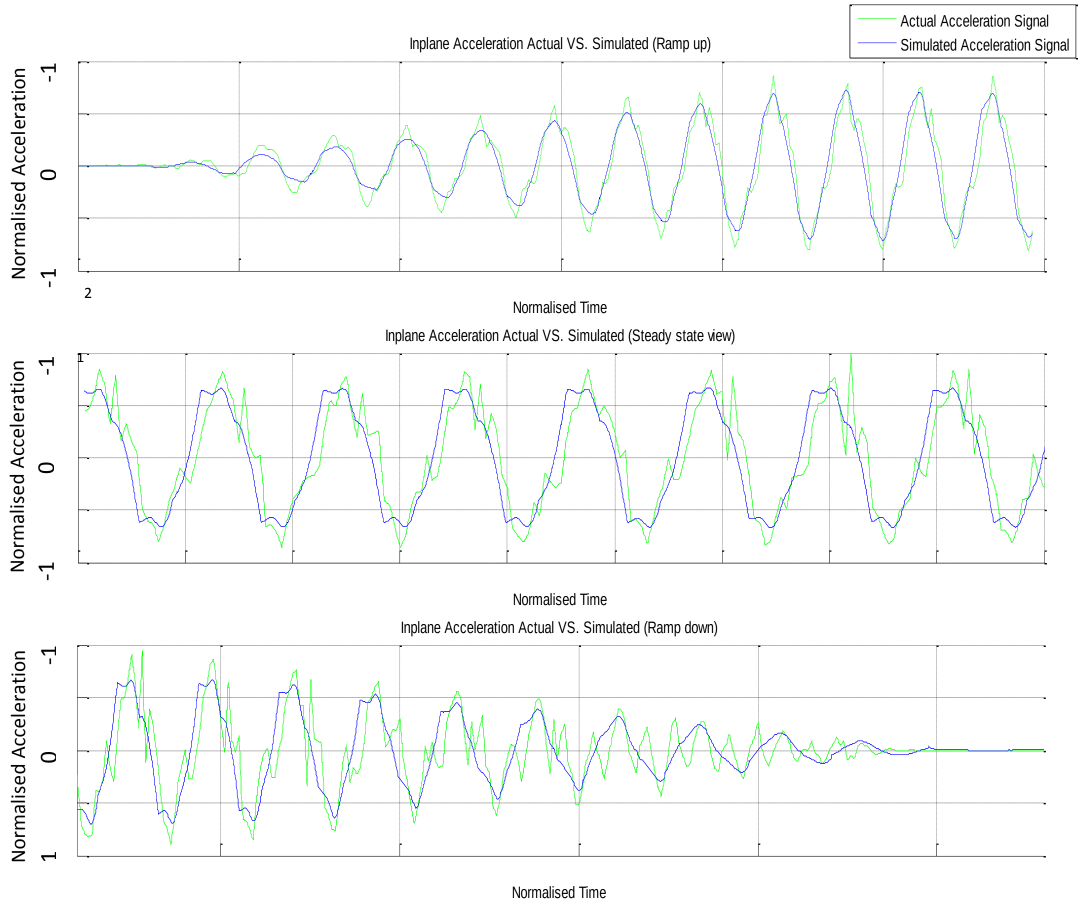

Figure 88 - In-plane Acceleration Time Series zoomed in

The C1 resonator pressure NRMSE is shown in figure 89. The NRMSE results are good averaging 8% with the maximum of data set 14 at 8.5%:

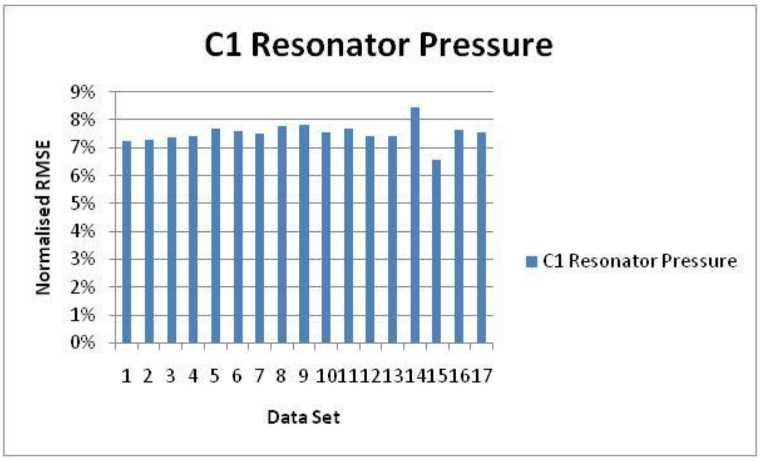

Figure 89 - C1 Resonator NRSE

The time series data can be seen in figures 90 and 91. The modelled response of this signal is very good.

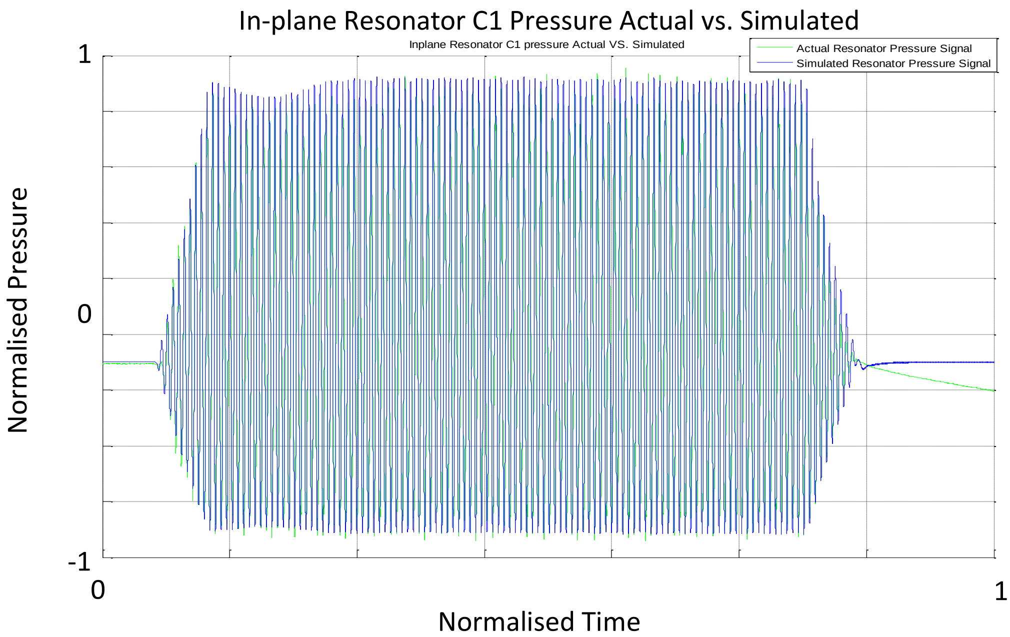

Figure 90 - C1 Resonator Time Series

In-plane resonator C1 pressure time series response zoomed in for data set 14:

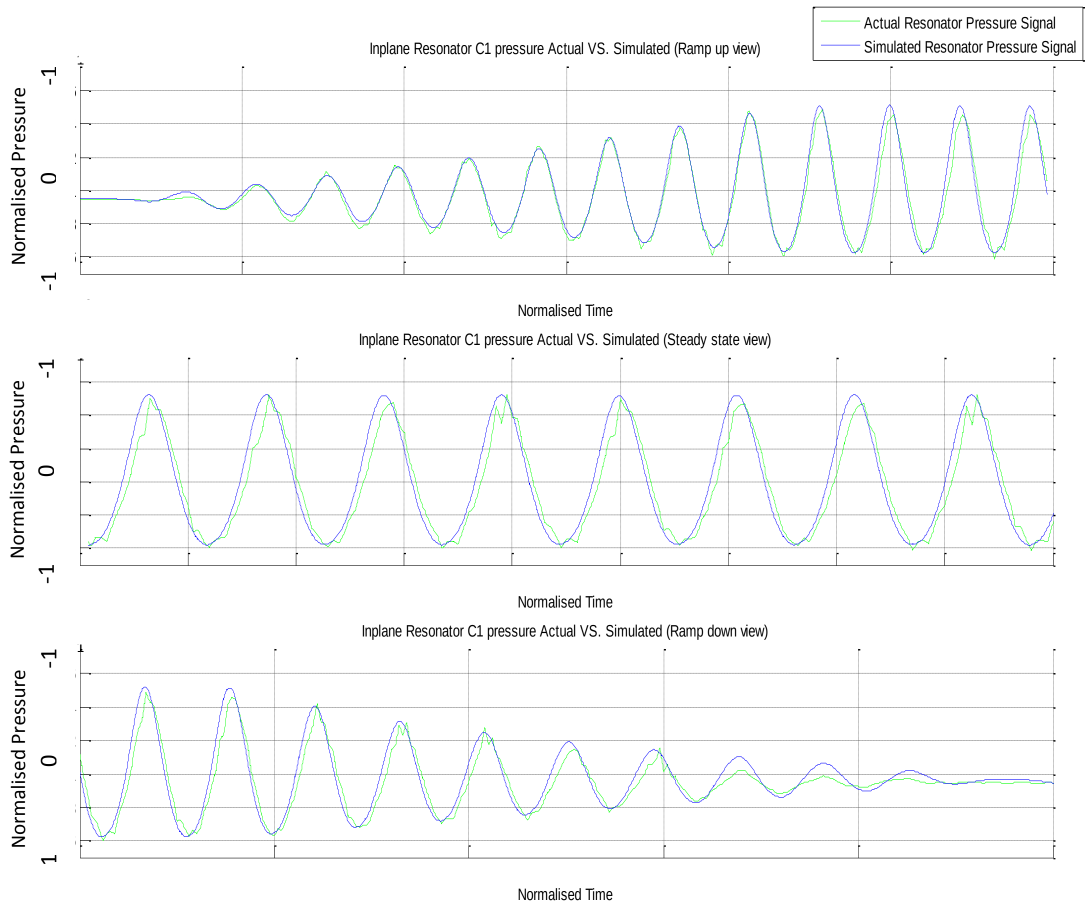

Figure 91 - C1 Resonator Time Series zoomed in

The C2 resonator pressure NRMSE is shown in figure 92, averaging 7% with the maximum of data set 14 at 8% indicating a good modelled response.

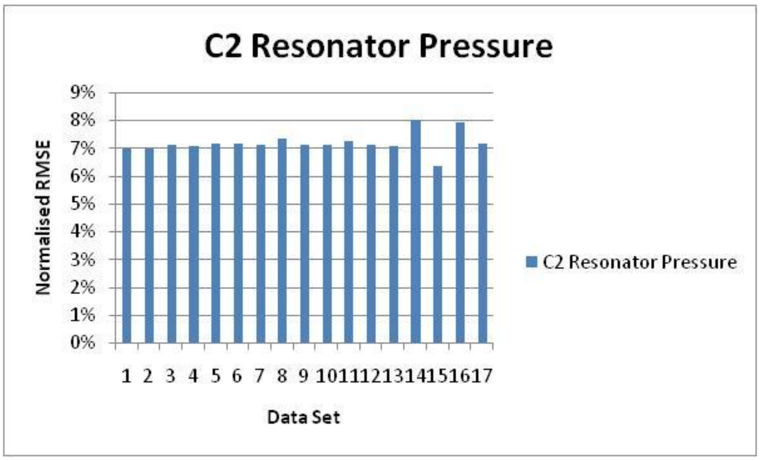

Figure 92 - Resonator C2 Pressure NRMSE

The time series response can be seen in figures 93 and 94 for data set 14:

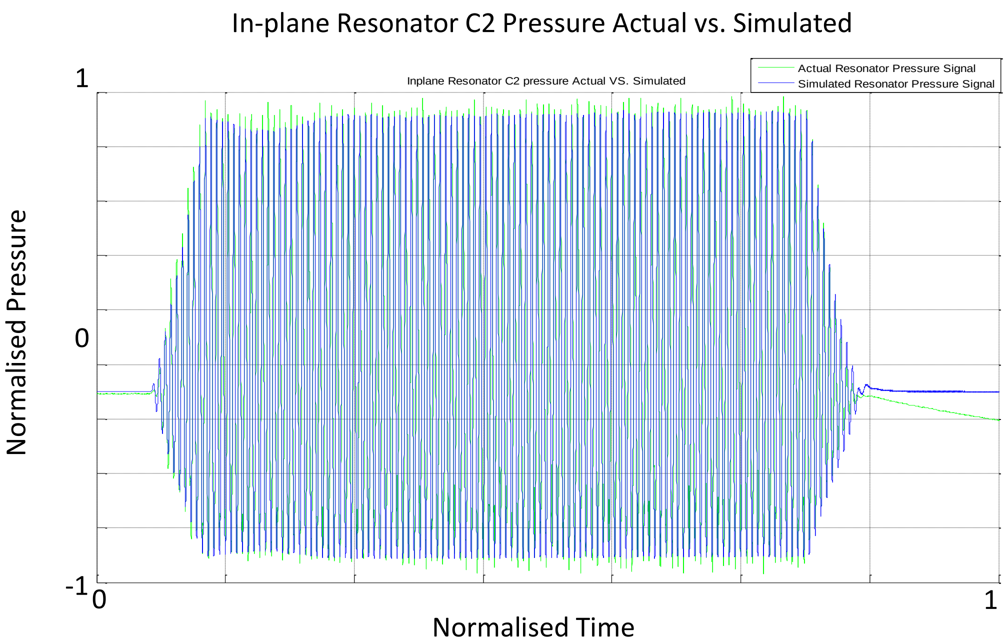

Figure 93 - In-plane Resonator C2 Pressure Time Series

In-plane resonator C2 pressure zoomed in:

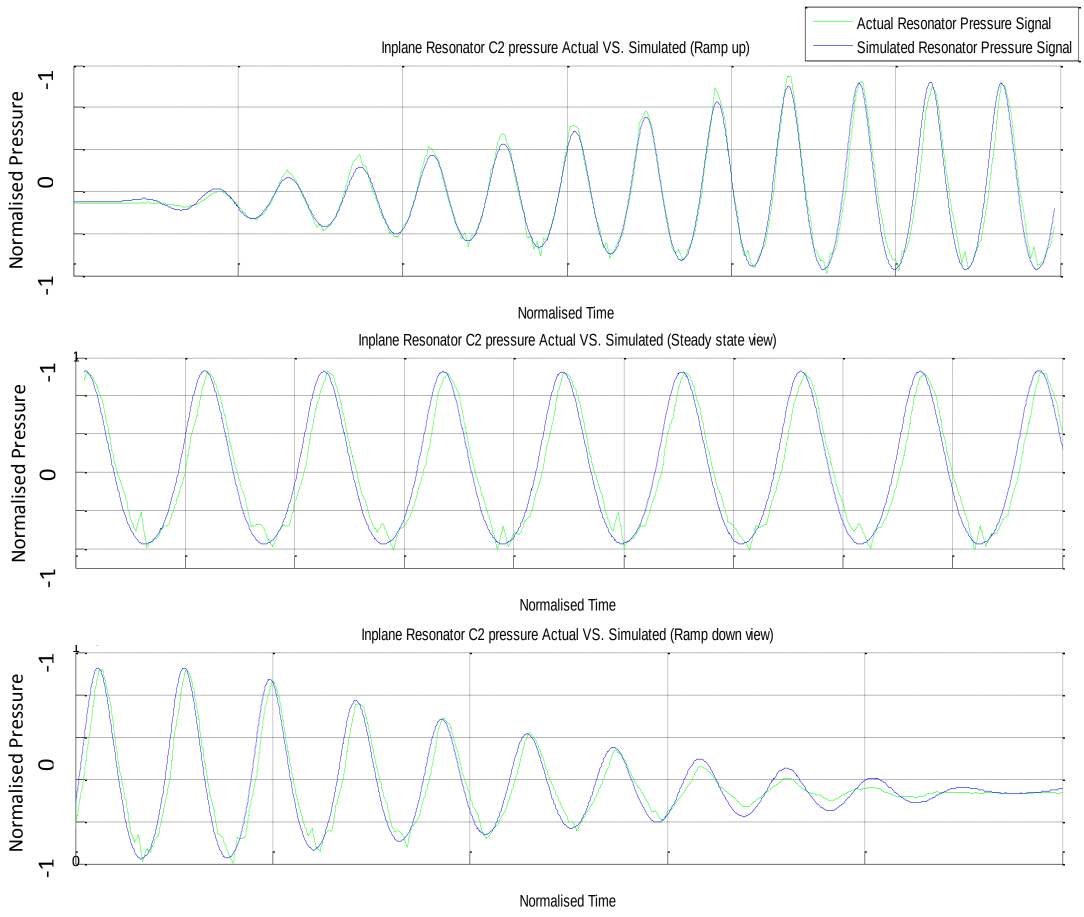

Figure 94 - In-plane Resonator C2 Pressure Time Series zoomed in

The C1 Resonator position is shown in figure 95, averages about 37% with the highest being data set 12.

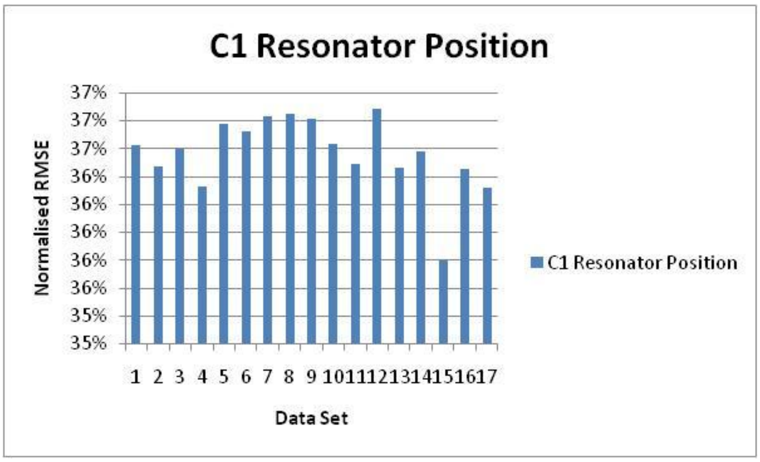

Figure 95 - Resonator C1 Position NRMS

The high NRMSE values are due to a constant amplitude shift seen throughout the data which is observable is the time series data shown in figures 96 and 97 for the 12th data set.

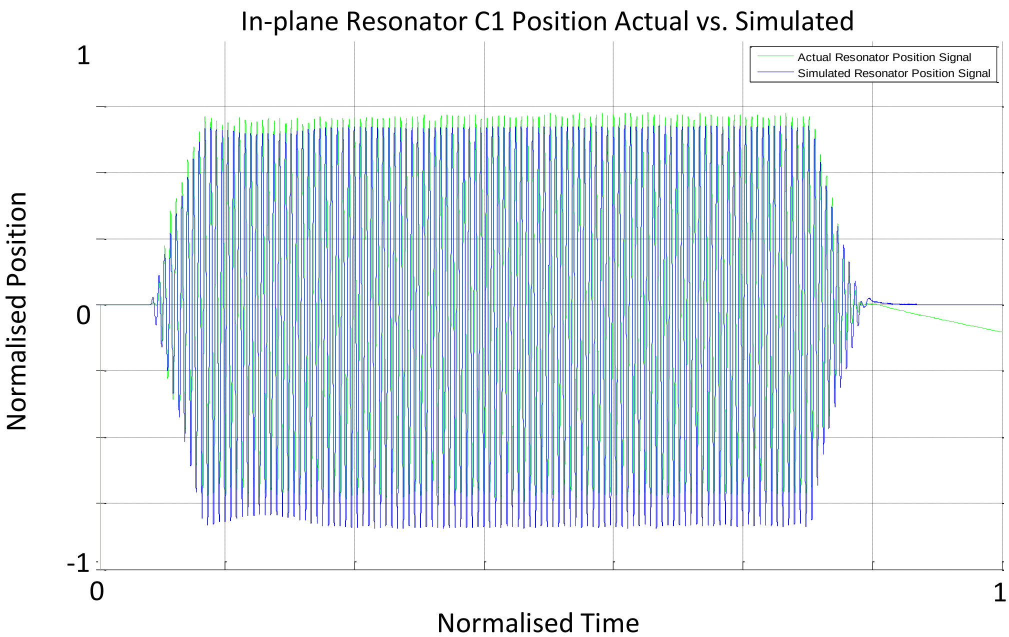

Figure 96 - In-plane Resonator C1 Position Time Series

In-plane resonator C1 position zoomed in time series:

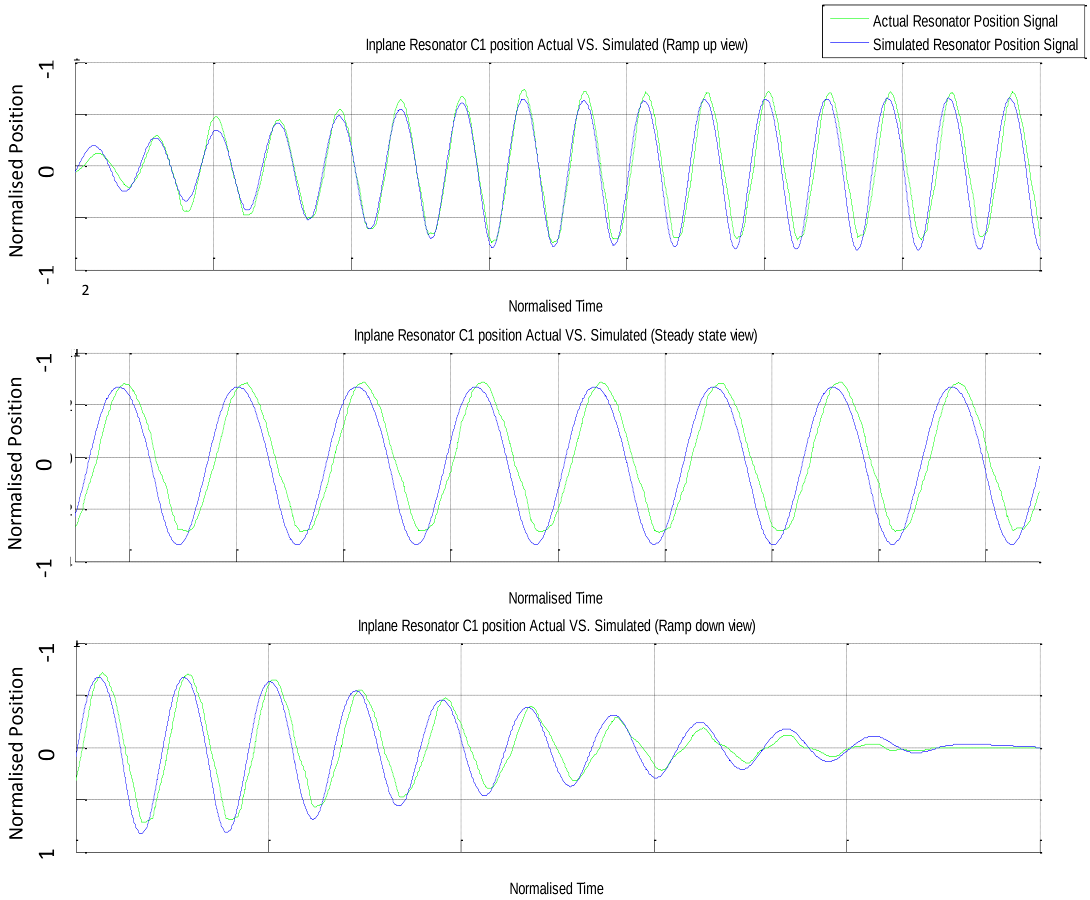

Figure 97 - In-plane Resonator C1 Position Time Series zoomed in

The C2 Resonator position is shown in figure 98, averages about 40% with the highest being data set 12.

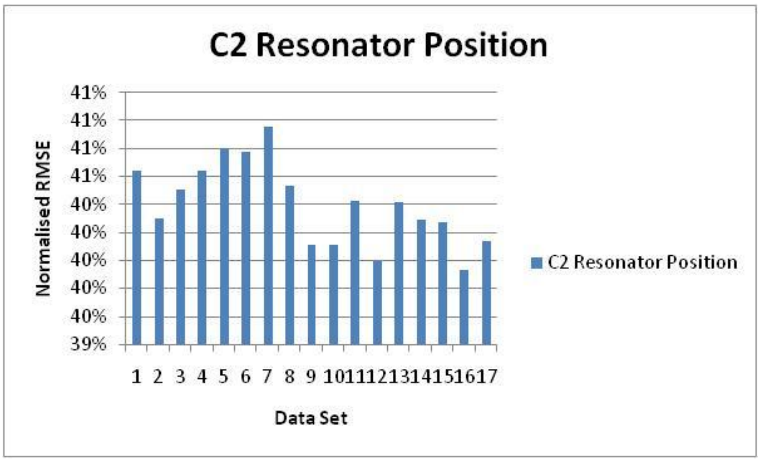

Figure 98 - In-plane C2 Resonator Position NRMSE

Figures 99 and 100 show the times series for the worse data set, again the constant amplitude shift can be seen throughout the data.

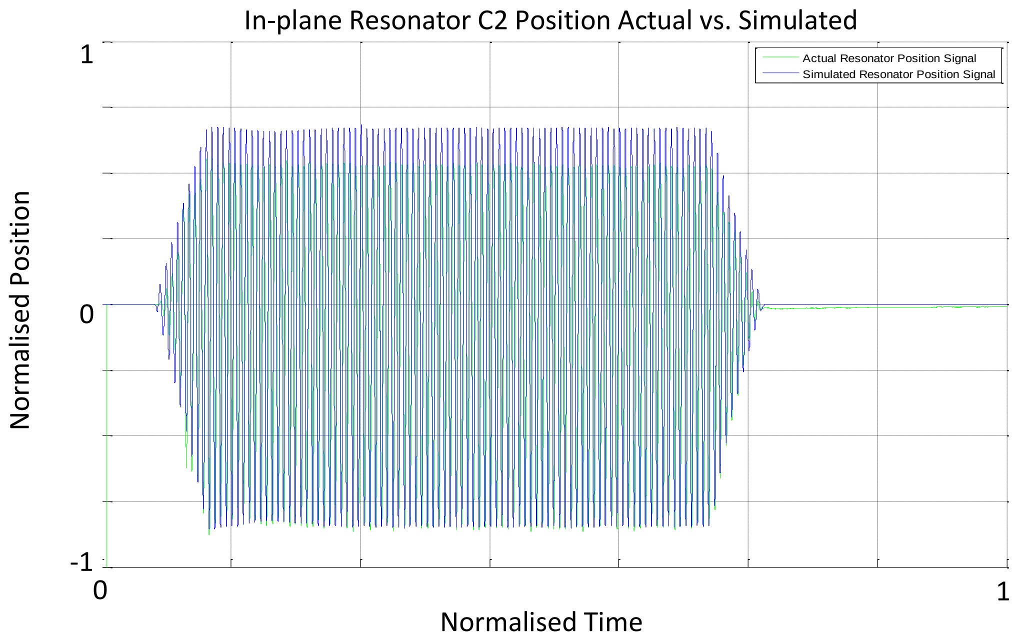

Figure 99 - In-plane C2 Resonator Position Time Series

In-plane resonator C2 zoomed in time series response for data set 12:

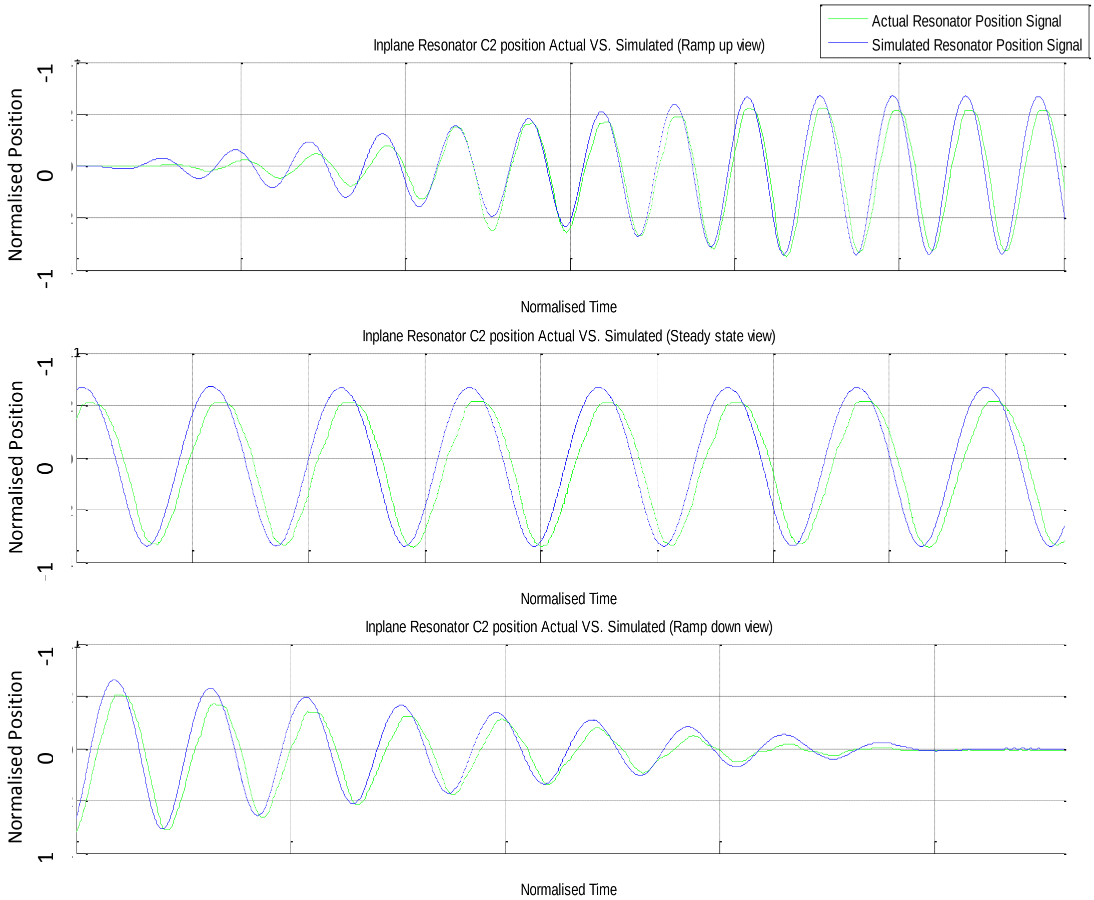

Figure 100 - In-plane C2 Resonator Position Time Series zoomed in

Figure 101 shows the NRMSE for the in-plane value displacement signal, the average is about 18% with data set 14 being the highest at 21%.

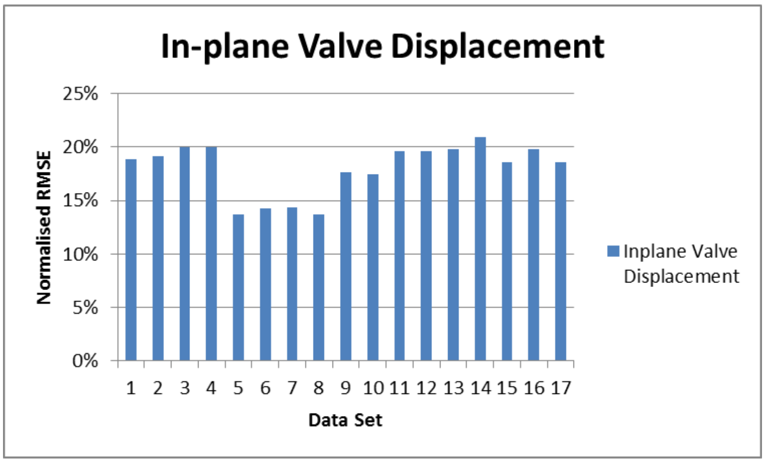

Figure 101 - In-plane Valve Displacement

The time series data for the worse data set is shown in figures 102 and 103, the main cause for the increase NRMSE is due to an amplitude difference throughout the signal.

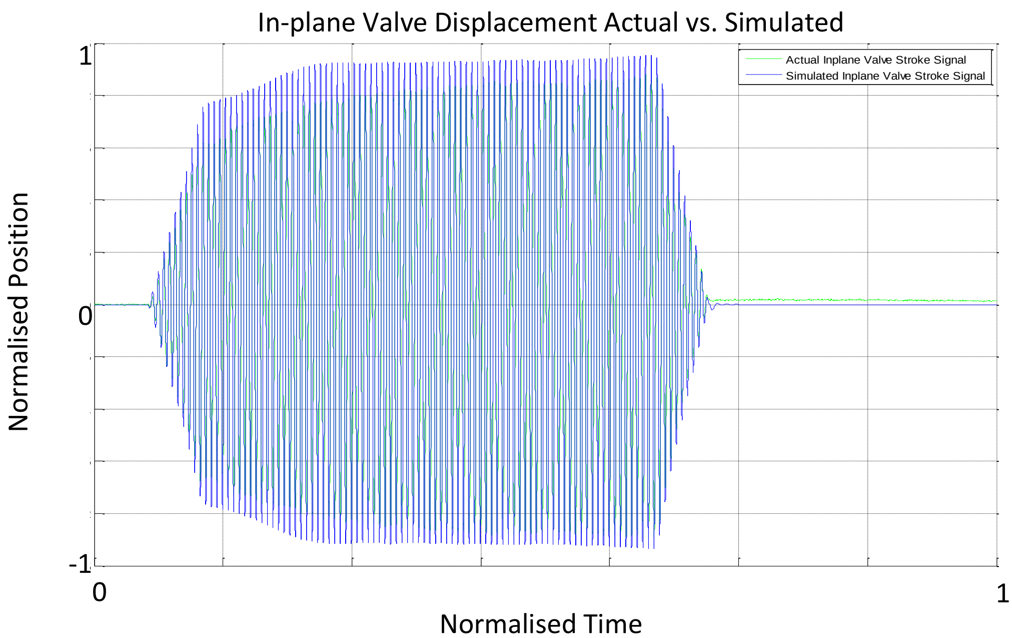

Figure 102 - In-plane Valve Displacement Time Series

In-plane valve displacement zoomed in time series response for data set 14:

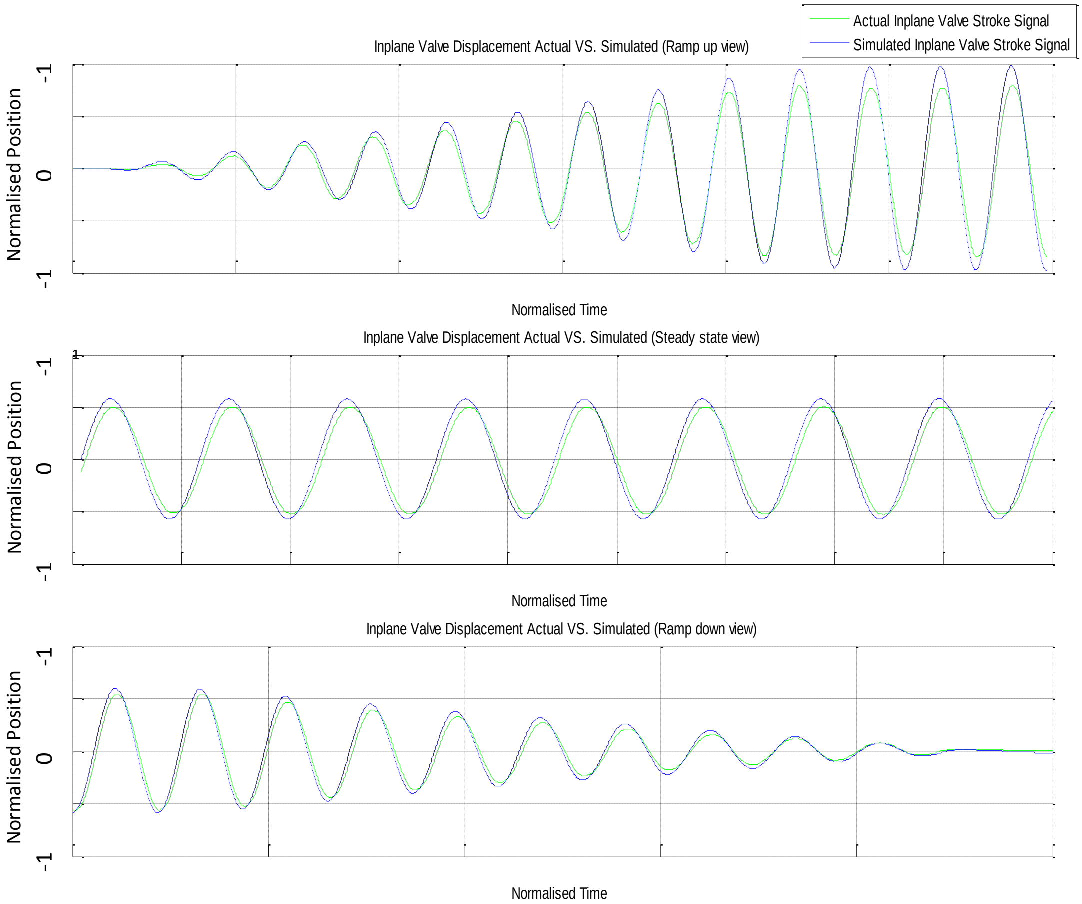

Figure 103 - In-plane Valve Displacement Time Series zoomed in

Figure 104 shows the NRMSE for the in-plane servo drive signal, the average is about 21% with data set 14 being the highest at 28%.

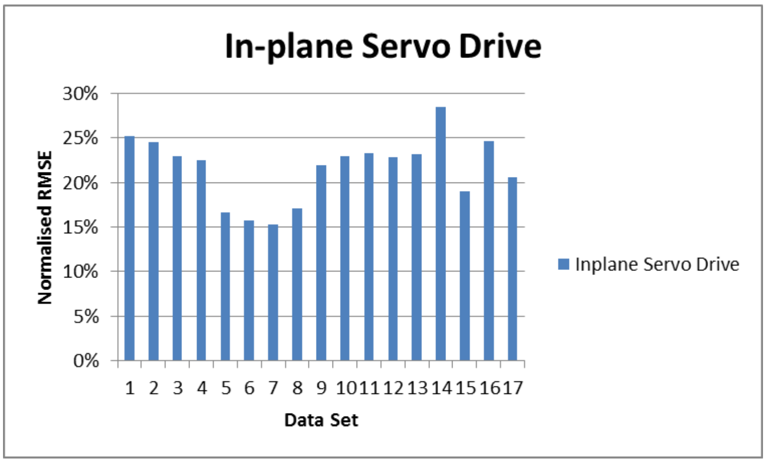

Figure 104 - In-plane Servo Drive NRMSE

Time series response data for the in-plane servo drive data set 14 can be seen in figure 105:

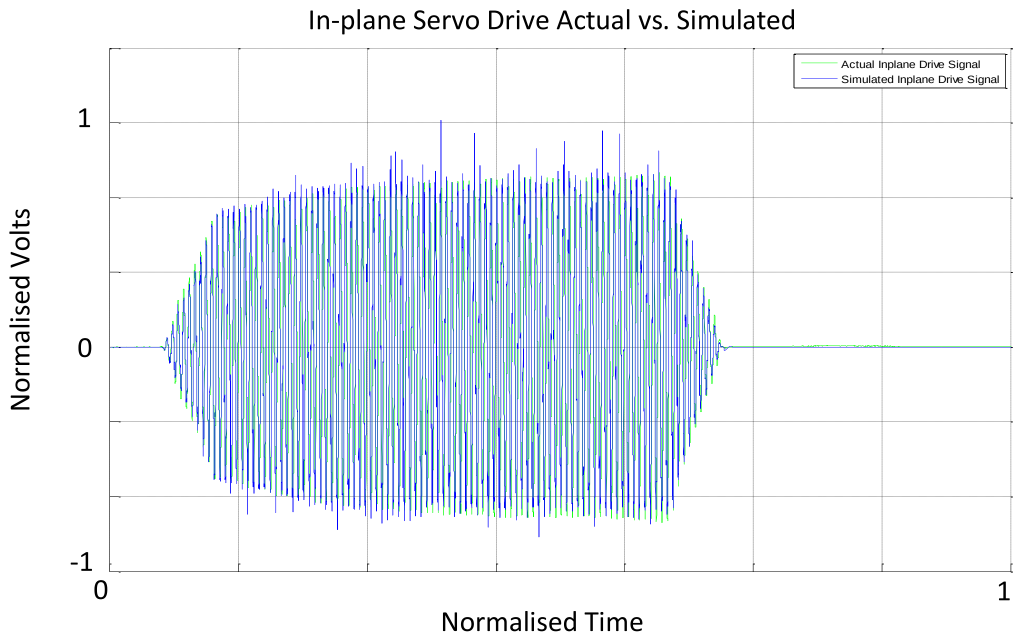

Figure 105 - In-plane Servo Drive Time Series

In-plane servo drive zoomed in time series response for data set 14:

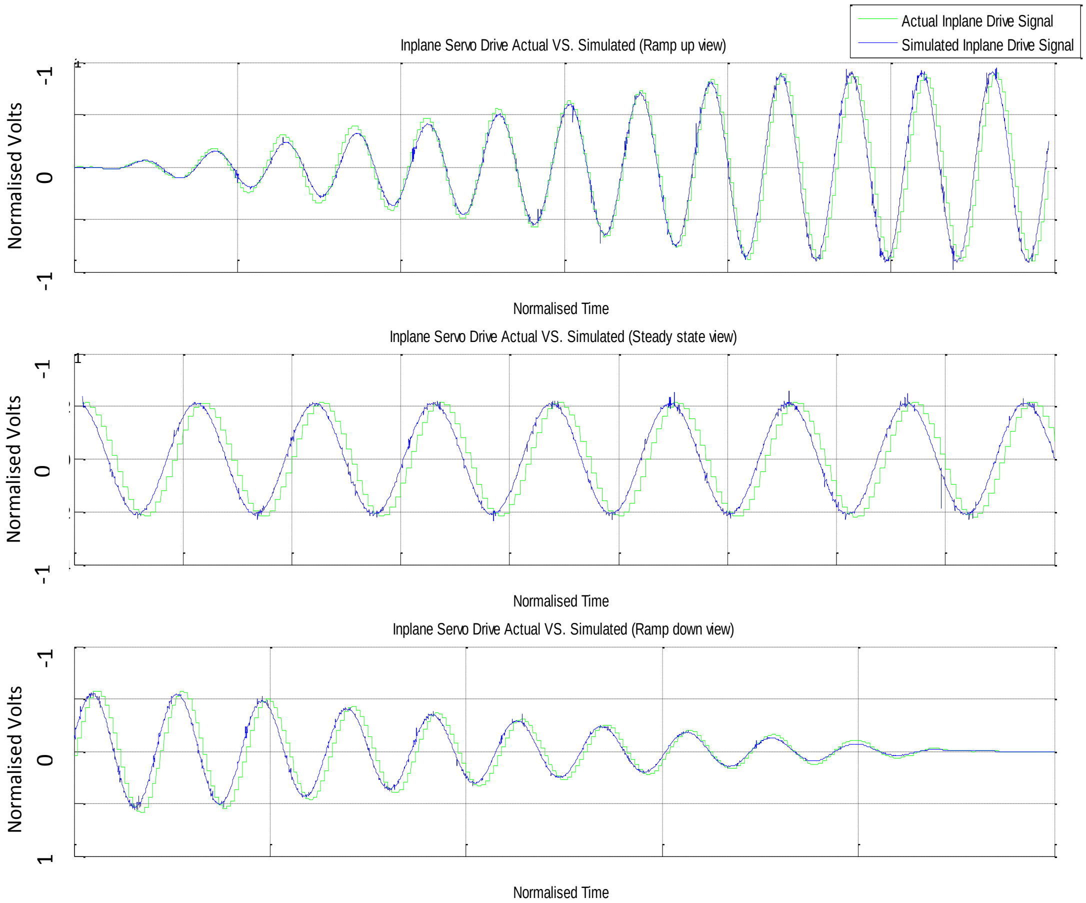

Figure 106 - In-plane Servo Drive Time Series zoomed in

Appendix 5 – Remaining Amplitude Ratio and Phase Difference Results

This Appendix reviews the remaining amplitude ratio and phase difference results from chapter 5 section 5.2.3.2.

The in-plane Acceleration AR and PD results are shown in figure 107, these results are both within the defined limits throughout the validation data sets.

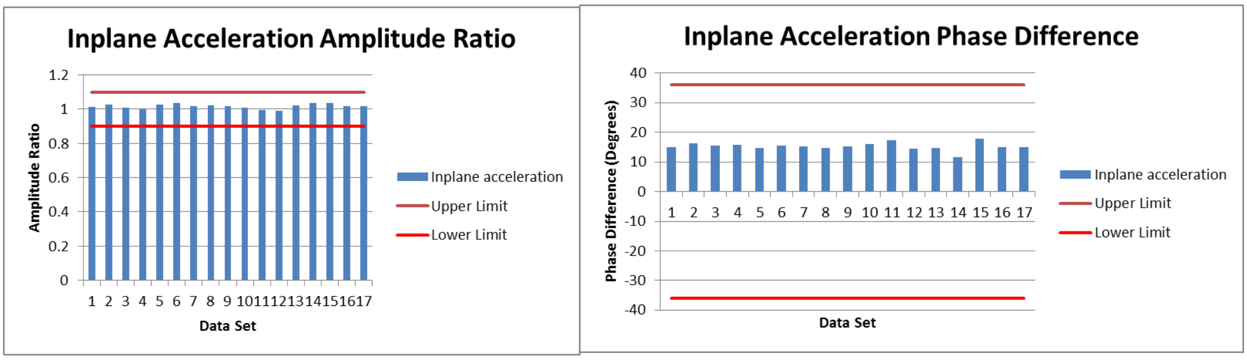

Figure 107 - In-plane Acceleration AR and PD

The C1 and C2 resonator pressures and positions AR and PD results are found in figures 108 to 111, a few of the validation data sets appear out of the limits. The model of the LF60 outputs what the resonator should be doing under normal conditions, it is known that overtime and also under different welding inputs or parameters the resonators performance changes, this would account for the variation observed.

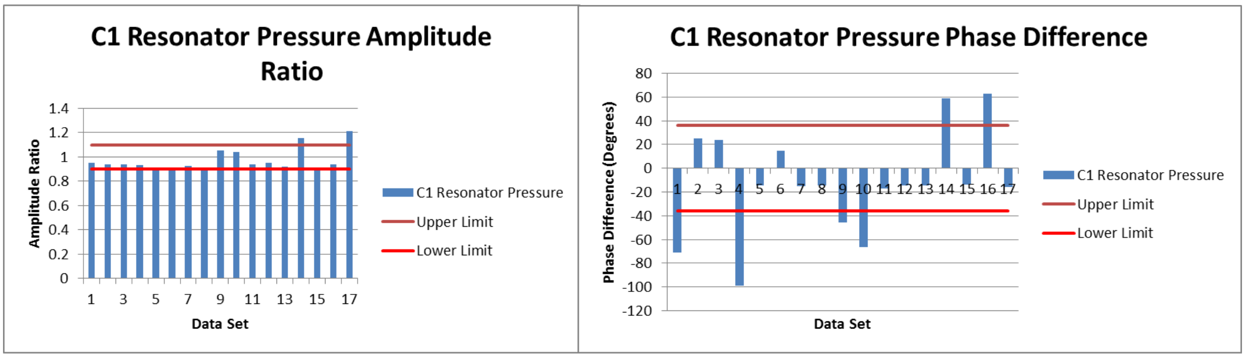

Figure 108 - In-plane Resonator C1 AR and PD

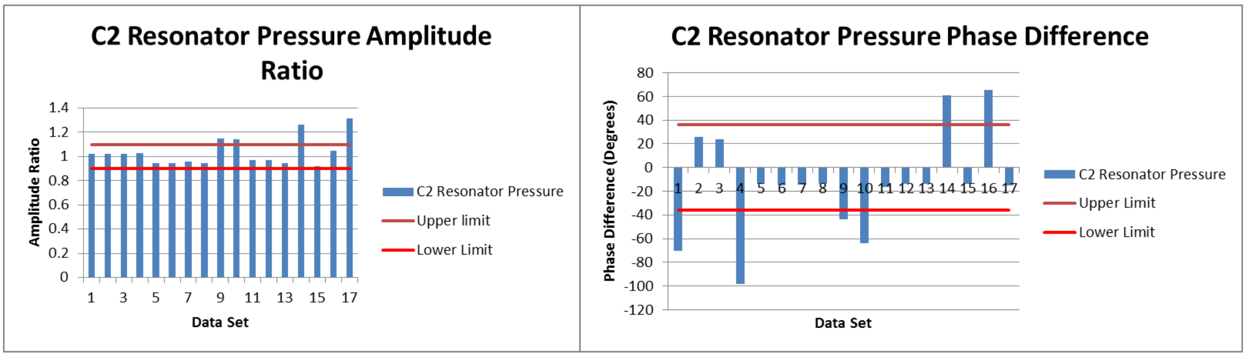

Figure 109 - Resonator C2 Pressure AR and PD

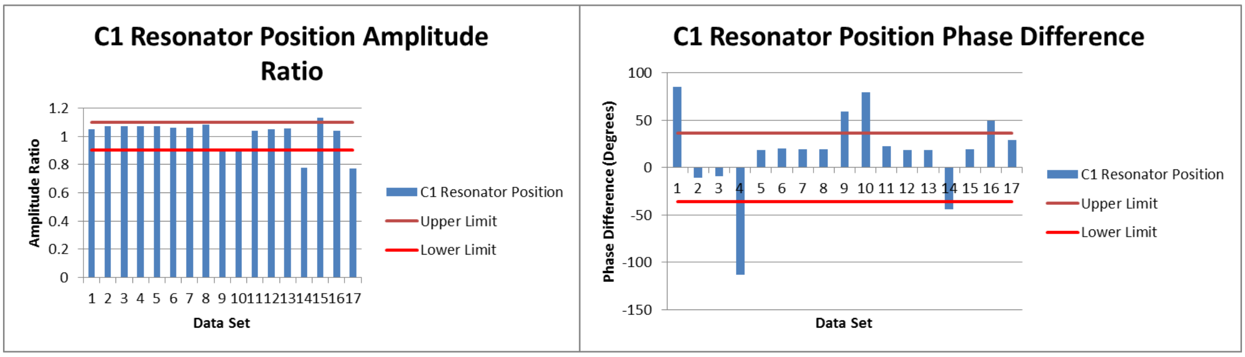

Figure 110 - Resonator C1 Position AR and PD

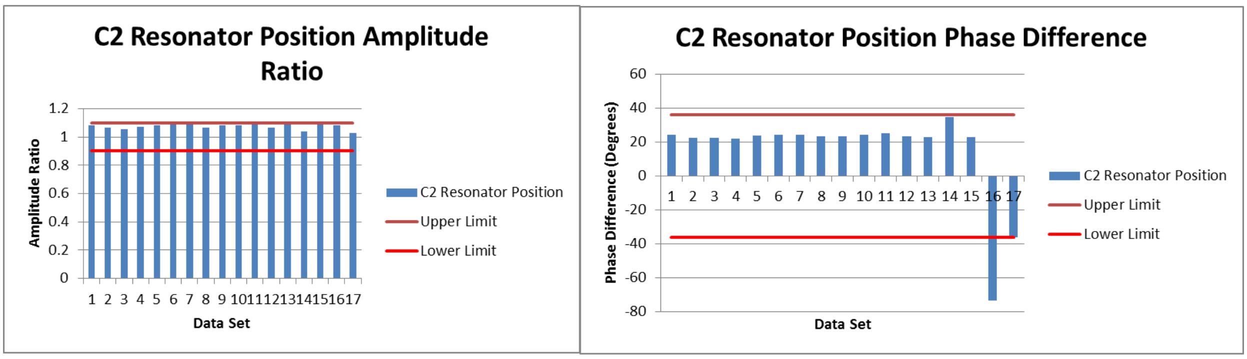

Figure 111 - In-plane C2 Resonator Position AR and PD

The in-plane servo drive AR and PD is shown in figure 112. Five results are out of the defined tolerance for the AR results. Four of these results are grouped in the 2nd component data set, and the other in the CAP data set thus the welding geometries and input parameters are effecting the accuracy of the models output.

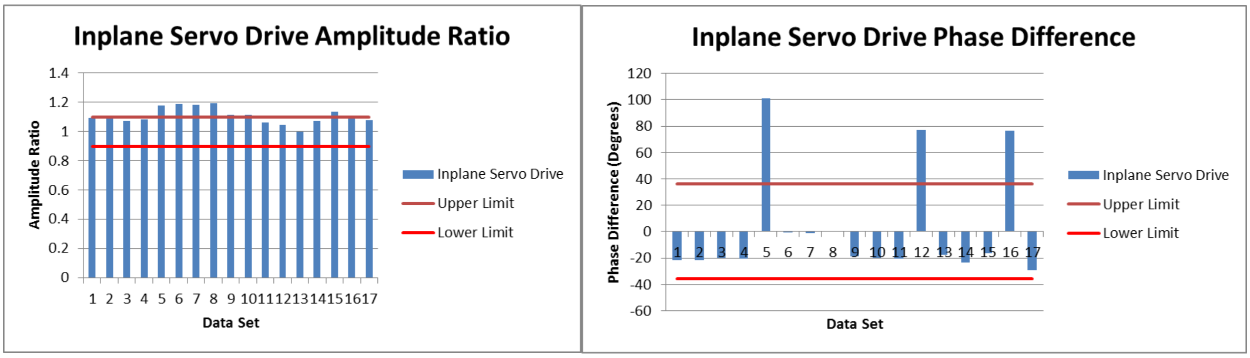

Figure 112 - In-plane Servo Drive AR and PD

The in-plane valve displacement results are shown in figure 113, only a couple of the results appear out of the defined tolerances, again the validated result differences are due to material and machine differences across the different welds.

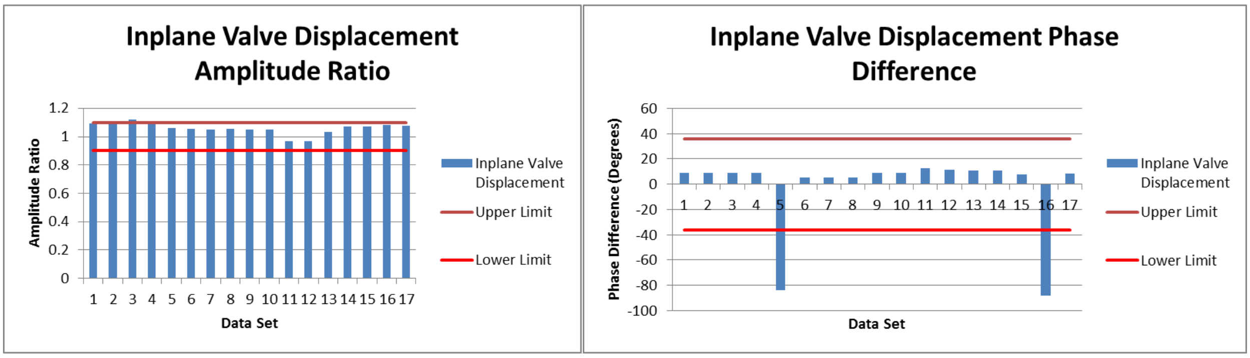

Figure 113 - In-plane Valve Displacement AR and PD

Appendix 6 – Adaptive Residual Limit Development

This appendix outlines the methods used to create the adaptive residual limits discussed in chapter 6, section 6.2.

The steps needed to calculate the Adaptive Residual Limit database are outlined as follows:

1. Execute the in-plane simulation model to save all the relevant variables to the Matlab workspace for an ok weld.
2. Execute the Residual Creator script which carries out the following:
    a. Simulates the Get_threshold_variables Simulink model to calculate the difference between the actual and modelled signals. See figure 115 – Get_threshold_variables (Example of a single variable).
    b. Runs through part of the script to sort through the variables and create the limit saved data
    c. Simulates the Define_residuals Simulink model to calculate the residual limit from the ok weld, and stores the limit in a database (mat file) which can be appended given further simulations. See figure 116 – Define_residuals (Example of a single variable).
3. Once a series of ok welds have been processed through the residual creation models the residual limit is ready to be used for fault diagnosis and isolation.

Figure 114 shows an example of simulating test data with residual limits, the upper figure shows the residual (difference of actual vs. modelled signal), the 2nd figure shows the residual limit captured from the residual in the forward direction, the 3rd figure shows the residual limit captured from the residual signal in the reverse direction. Functions in the residual creator script enable the combination of the forward and reverse residual limit to be combined together to give the bottom figure, which shows the residual limit defined from the residual signal in the forward direction. This residual limit value is used for the fault detection purposes, to capture faults.

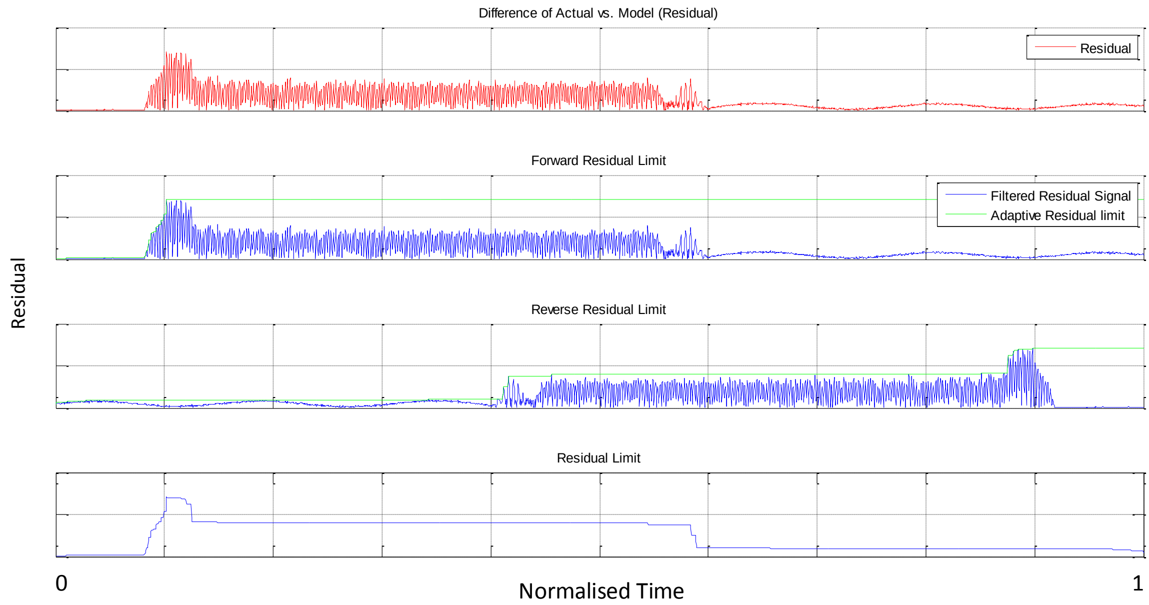

Figure 114 - Outputs simulating data with residual limits

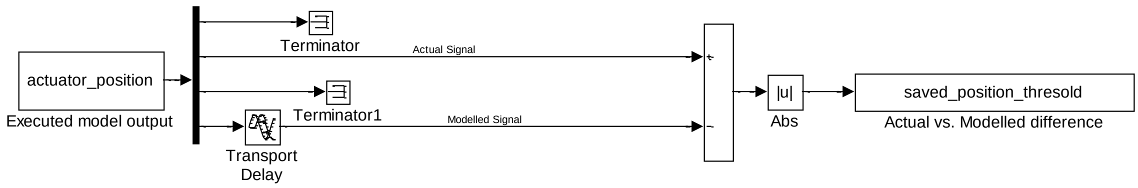

Figure 115 - Get_threshold_variables model (Example of a single variable)

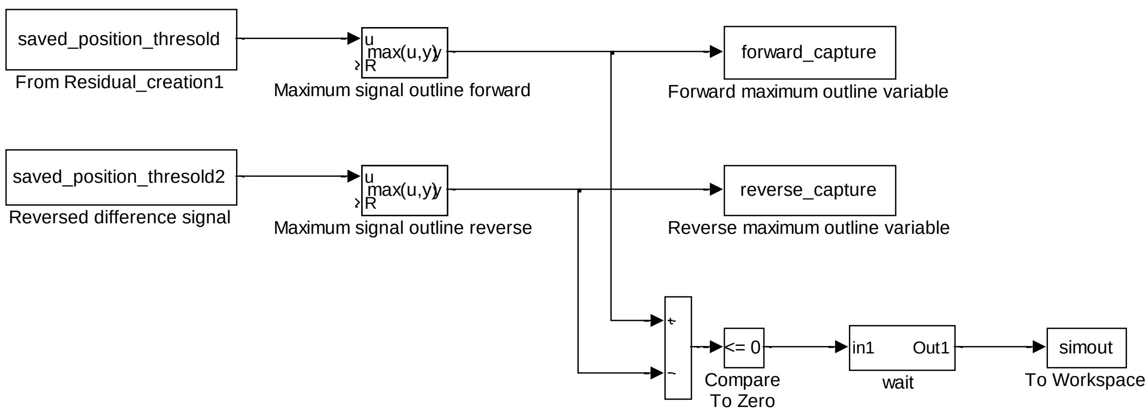

Figure 116 - Define_residuals model (Example of a single variable)

The residual creator script follows:

```
% This script enables the creation of the residual limits, prior to
% executing the script, OK weld data should have been executed
% through the in-plane model.
%
% Darren Williams - Sept/2012


%% Simulates the model needed to get each of the threshold variables
open('Get_threshold_variables')
sim('Get_threshold_variables')

%% This section sorts the position thresholds
%Create variables for later use
saved_position_thresold2=saved_position_thresold;
residual1=saved_position_thresold;
%This checks if a limit database exists, if so it can be opened to
be appended to,
%otherwise one will be created
if exist('component_limit_residual.mat','file') == 0
    saved_residuals=saved_position_thresold;
    %Makes the non needed entries zero
    for i=1:length(saved_position_thresold.signals.values)
        saved_residuals.signals.values(i)=0;
    end
    save('component_limit_residual.mat','saved_residuals')
end
%This reverses the residual signal
n=0;
for i=1:length(saved_position_thresold.signals.values);%reverse

saved_position_thresold2.signals.values(i)=saved_position_thresold.s
ignals.values(end-n);
    n=i;
end
load('component_limit_residual.mat','saved_residuals')%load limits

%% This section sorts the force thresholds - not commented as
duplicate of above
saved_force_thresold2=saved_force_thresold;
residual1=saved_force_thresold;
if exist('component_limit_residual2.mat','file') == 0
    saved_residuals1=saved_force_thresold;
    for i=1:length(saved_force_thresold.signals.values)
        saved_residuals1.signals.values(i)=0;
    end
    save('component_limit_residual2.mat','saved_residuals1')
end
n=0;
for i=1:length(saved_force_thresold.signals.values);

saved_force_thresold2.signals.values(i)=saved_force_thresold.signals
.values(end-n);
    n=i;
end
load('component_limit_residual2.mat','saved_residuals1')
%% This section sorts the acceleration thresholds
saved_acceleration_thresold2=saved_acceleration_thresold;
residual1=saved_acceleration_thresold;
```

```
if exist('component_limit_residual3.mat','file') == 0
    saved_residuals2=saved_acceleration_thresold;
    for i=1:length(saved_acceleration_thresold.signals.values)
        saved_residuals2.signals.values(i)=0;
    end
    save('component_limit_residual3.mat','saved_residuals2')
end
n=0;
for i=1:length(saved_acceleration_thresold.signals.values);

saved_acceleration_thresold2.signals.values(i)=saved_acceleration_th
resold.signals.values(end-n);
    n=i;
end
load('component_limit_residual3.mat','saved_residuals2')
%% This section sorts the actc1 thresholds
saved_actc1_thresold2=saved_actc1_thresold;
residual1=saved_actc1_thresold;
if exist('component_limit_residual4.mat','file') == 0
    saved_residuals3=saved_actc1_thresold;
    for i=1:length(saved_actc1_thresold.signals.values)
        saved_residuals3.signals.values(i)=0;
    end
    save('component_limit_residual4.mat','saved_residuals3')
end
n=0;
for i=1:length(saved_actc1_thresold.signals.values);

saved_actc1_thresold2.signals.values(i)=saved_actc1_thresold.signals
.values(end-n);
    n=i;
end
load('component_limit_residual4.mat','saved_residuals3')
%% This section sorts the actc2 thresholds
saved_actc2_thresold2=saved_actc2_thresold;
residual1=saved_actc2_thresold;
if exist('component_limit_residual5.mat','file') == 0
    saved_residuals4=saved_actc2_thresold;
    for i=1:length(saved_actc2_thresold.signals.values)
        saved_residuals4.signals.values(i)=0;
    end
    save('component_limit_residual5.mat','saved_residuals4')
end
n=0;
for i=1:length(saved_actc2_thresold.signals.values);

saved_actc2_thresold2.signals.values(i)=saved_actc2_thresold.signals
.values(end-n);
    n=i;
end
load('component_limit_residual5.mat','saved_residuals4')
%% This section sorts the resonator load thresholds
saved_resload_thresold2=saved_resload_thresold;
residual1=saved_resload_thresold;
if exist('component_limit_residual6.mat','file') == 0
    saved_residuals5=saved_resload_thresold;
    for i=1:length(saved_resload_thresold.signals.values)
        saved_residuals5.signals.values(i)=0;
    end
    save('component_limit_residual6.mat','saved_residuals5')
end
```

```
n=0;
for i=1:length(saved_resload_thresold.signals.values);

saved_resload_thresold2.signals.values(i)=saved_resload_thresold.sig
nals.values(end-n);
    n=i;
end
load('component_limit_residual6.mat','saved_residuals5')
%% This section sorts the resonator pressure1 thresholds
saved_res_press1_thresold2=saved_res_press1_thresold;
residual1=saved_res_press1_thresold;
if exist('component_limit_residual7.mat','file') == 0
    saved_residuals6=saved_res_press1_thresold;
    for i=1:length(saved_res_press1_thresold.signals.values)
        saved_residuals6.signals.values(i)=0;
    end
    save('component_limit_residual7.mat','saved_residuals6')
end
n=0;
for i=1:length(saved_res_press1_thresold.signals.values);

saved_res_press1_thresold2.signals.values(i)=saved_res_press1_threso
ld.signals.values(end-n);
    n=i;
end
load('component_limit_residual7.mat','saved_residuals6')
%% This section sorts the resonator pressure 2 thresholds
saved_res_press2_thresold2=saved_res_press2_thresold;
residual1=saved_res_press2_thresold;
if exist('component_limit_residual8.mat','file') == 0
    saved_residuals7=saved_res_press2_thresold;
    for i=1:length(saved_res_press2_thresold.signals.values)
        saved_residuals7.signals.values(i)=0;
    end
    save('component_limit_residual8.mat','saved_residuals7')
end
n=0;
for i=1:length(saved_res_press2_thresold.signals.values);

saved_res_press2_thresold2.signals.values(i)=saved_res_press2_threso
ld.signals.values(end-n);
    n=i;
end
load('component_limit_residual8.mat','saved_residuals7')
%% This section sorts the resonator position2 thresholds
saved_res_poss2_thresold2=saved_res_poss2_thresold;
residual1=saved_res_poss2_thresold;
if exist('component_limit_residual9.mat','file') == 0
    saved_residuals8=saved_res_poss2_thresold;
    for i=1:length(saved_res_poss2_thresold.signals.values)
        saved_residuals8.signals.values(i)=0;
    end
    save('component_limit_residual9.mat','saved_residuals8')
end
n=0;
for i=1:length(saved_res_poss2_thresold.signals.values);

saved_res_poss2_thresold2.signals.values(i)=saved_res_poss2_thresold
.signals.values(end-n);
    n=i;
end
```

```
load('component_limit_residual9.mat','saved_residuals8')
%% This section sorts the resonator position 1 thresholds
saved_res_poss1_thresold2=saved_res_poss1_thresold;
residual1=saved_res_poss1_thresold;
if exist('component_limit_residual10.mat','file') == 0
    saved_residuals9=saved_res_poss1_thresold;
    for i=1:length(saved_res_poss1_thresold.signals.values)
        saved_residuals9.signals.values(i)=0;
    end
    save('component_limit_residual10.mat','saved_residuals9')
end
n=0;
for i=1:length(saved_res_poss1_thresold.signals.values);

saved_res_poss1_thresold2.signals.values(i)=saved_res_poss1_thresold
.signals.values(end-n);
    n=i;
end
load('component_limit_residual10.mat','saved_residuals9')
%% This section sorts the actuator stroke thresholds
saved_stroke_thresold2=saved_stroke_thresold;
residual1=saved_stroke_thresold;
if exist('component_limit_residual11.mat','file') == 0
    saved_residuals10=saved_stroke_thresold;
    for i=1:length(saved_stroke_thresold.signals.values)
        saved_residuals10.signals.values(i)=0;
    end
    save('component_limit_residual11.mat','saved_residuals10')
end
n=0;
for i=1:length(saved_stroke_thresold.signals.values);

saved_stroke_thresold2.signals.values(i)=saved_stroke_thresold.signa
ls.values(end-n);
    n=i;
end
load('component_limit_residual11.mat','saved_residuals10')
%% This section sorts the servo thresholds
saved_servo_thresold2=saved_servo_thresold;
residual1=saved_servo_thresold;
if exist('component_limit_residual12.mat','file') == 0
    saved_residuals11=saved_servo_thresold;
    for i=1:length(saved_servo_thresold.signals.values)
        saved_residuals11.signals.values(i)=0;
    end
    save('component_limit_residual12.mat','saved_residuals11')
end
n=0;
for i=1:length(saved_servo_thresold.signals.values);

saved_servo_thresold2.signals.values(i)=saved_servo_thresold.signals
.values(end-n);
    n=i;
end
load('component_limit_residual12.mat','saved_residuals11')

%% Simulates the model which defines each of the residual variables
open('Define_residuals')
sim('Define_residuals')

%%For the position signal
```

```
%Makes the non needed entries zero
for
i=find(simout.signals.values,1):length(reverse_capture.signals.value
s);
    reverse_capture.signals.values(i)=0;
end
n=0;
for i=1:length(reverse_capture.signals.values);
    residual1.signals.values(i)=reverse_capture.signals.values(end-
n);
    n=i;
end
%Adds together the forward and reserve residual limits to create the
fault
%detection one
for i=1:(length(reverse_capture.signals.values)-
(find(simout.signals.values,1)-1));
    residual1.signals.values(i)=forward_capture.signals.values(i);
end
%This gets the maximum of either the new, or stored residual limit
and then
%saves it into the database
saved_residuals.signals.values=max(residual1.signals.values,saved_re
siduals.signals.values);
save('component_limit_residual.mat','saved_residuals')%update limits
window
%%For the load signal - not commented as duplicate to above
for
i=find(simout1.signals.values,1):length(reverse_capture1.signals.val
ues);
    reverse_capture1.signals.values(i)=0;
end
n=0;
for i=1:length(reverse_capture1.signals.values);
    residual1.signals.values(i)=reverse_capture1.signals.values(end-
n);
    n=i;
end
for i=1:(length(reverse_capture1.signals.values)-
(find(simout1.signals.values,1)-1));
    residual1.signals.values(i)=forward_capture1.signals.values(i);
end
saved_residuals1.signals.values=max(residual1.signals.values,saved_r
esiduals1.signals.values);
save('component_limit_residual2.mat','saved_residuals1')
%%For the accel signal - not commented as duplicate to above
for
i=find(simout2.signals.values,1):length(reverse_capture2.signals.val
ues);
    reverse_capture2.signals.values(i)=0;
end
n=0;
for i=1:length(reverse_capture2.signals.values);
    residual1.signals.values(i)=reverse_capture2.signals.values(end-
n);
    n=i;
end
for i=1:(length(reverse_capture2.signals.values)-
(find(simout2.signals.values,1)-1));
    residual1.signals.values(i)=forward_capture2.signals.values(i);
end
```

```
saved_residuals2.signals.values=max(residual1.signals.values,saved_r
esiduals2.signals.values);
save('component_limit_residual3.mat','saved_residuals2')
%%For the actc1 signal - not commented as duplicate to above
for
i=find(simout3.signals.values,1):length(reverse_capture3.signals.val
ues);
    reverse_capture3.signals.values(i)=0;
end
n=0;
for i=1:length(reverse_capture3.signals.values);
    residual1.signals.values(i)=reverse_capture3.signals.values(end-
n);
    n=i;
end
for i=1:(length(reverse_capture3.signals.values)-
(find(simout3.signals.values,1)-1));
    residual1.signals.values(i)=forward_capture3.signals.values(i);
end
saved_residuals3.signals.values=max(residual1.signals.values,saved_r
esiduals3.signals.values);
save('component_limit_residual4.mat','saved_residuals3')
%%For the actc2 signal - not commented as duplicate to above
for
i=find(simout4.signals.values,1):length(reverse_capture4.signals.val
ues);
    reverse_capture4.signals.values(i)=0;
end
n=0;
for i=1:length(reverse_capture4.signals.values);
    residual1.signals.values(i)=reverse_capture4.signals.values(end-
n);
    n=i;
end
for i=1:(length(reverse_capture4.signals.values)-
(find(simout4.signals.values,1)-1));
    residual1.signals.values(i)=forward_capture4.signals.values(i);
end
saved_residuals4.signals.values=max(residual1.signals.values,saved_r
esiduals4.signals.values);
save('component_limit_residual5.mat','saved_residuals4')
%%For the resload signal - not commented as duplicate to above
for
i=find(simout5.signals.values,1):length(reverse_capture5.signals.val
ues);
    reverse_capture5.signals.values(i)=0;
end
n=0;
for i=1:length(reverse_capture5.signals.values);
    residual1.signals.values(i)=reverse_capture5.signals.values(end-
n);
    n=i;
end
for i=1:(length(reverse_capture5.signals.values)-
(find(simout5.signals.values,1)-1));
    residual1.signals.values(i)=forward_capture5.signals.values(i);
end
saved_residuals5.signals.values=max(residual1.signals.values,saved_r
esiduals5.signals.values);
save('component_limit_residual6.mat','saved_residuals5')
```

```
%%For the res c1 pressure signal - not commented as duplicate to
above
for
i=find(simout6.signals.values,1):length(reverse_capture6.signals.val
ues);
    reverse_capture6.signals.values(i)=0;
end
n=0;
for i=1:length(reverse_capture6.signals.values);
    residual1.signals.values(i)=reverse_capture6.signals.values(end-
n);
    n=i;
end
for i=1:(length(reverse_capture6.signals.values)-
(find(simout6.signals.values,1)-1));
    residual1.signals.values(i)=forward_capture6.signals.values(i);
end
saved_residuals6.signals.values=max(residual1.signals.values,saved_r
esiduals6.signals.values);
save('component_limit_residual7.mat','saved_residuals6')
%%For the res c2 pressure signal - not commented as duplicate to
above
for
i=find(simout7.signals.values,1):length(reverse_capture7.signals.val
ues);
    reverse_capture7.signals.values(i)=0;
end
n=0;
for i=1:length(reverse_capture7.signals.values);
    residual1.signals.values(i)=reverse_capture7.signals.values(end-
n);
    n=i;
end
for i=1:(length(reverse_capture7.signals.values)-
(find(simout7.signals.values,1)-1));
    residual1.signals.values(i)=forward_capture7.signals.values(i);
end
saved_residuals7.signals.values=max(residual1.signals.values,saved_r
esiduals7.signals.values);
save('component_limit_residual8.mat','saved_residuals7')
%%For the res c2 position signal - not commented as duplicate to
above
for
i=find(simout8.signals.values,1):length(reverse_capture8.signals.val
ues);
    reverse_capture8.signals.values(i)=0;
end
n=0;
for i=1:length(reverse_capture8.signals.values);
    residual1.signals.values(i)=reverse_capture8.signals.values(end-
n);
    n=i;
end
for i=1:(length(reverse_capture8.signals.values)-
(find(simout8.signals.values,1)-1));
    residual1.signals.values(i)=forward_capture8.signals.values(i);
end
saved_residuals8.signals.values=max(residual1.signals.values,saved_r
esiduals8.signals.values);
save('component_limit_residual9.mat','saved_residuals8')
```

```
%%For the res c1 position signal - not commented as duplicate to
above
for
i=find(simout9.signals.values,1):length(reverse_capture9.signals.val
ues);
    reverse_capture9.signals.values(i)=0;
end
n=0;
for i=1:length(reverse_capture9.signals.values);
    residual1.signals.values(i)=reverse_capture9.signals.values(end-
n);
    n=i;
end
for i=1:(length(reverse_capture9.signals.values)-
(find(simout9.signals.values,1)-1));
    residual1.signals.values(i)=forward_capture9.signals.values(i);
end
saved_residuals9.signals.values=max(residual1.signals.values,saved_r
esiduals9.signals.values);
save('component_limit_residual10.mat','saved_residuals9')
%%For the stroke displacement position signal - not commented as
duplicate to above
for
i=find(simout10.signals.values,1):length(reverse_capture10.signals.v
alues);
    reverse_capture10.signals.values(i)=0;
end
n=0;
for i=1:length(reverse_capture10.signals.values);

residual1.signals.values(i)=reverse_capture10.signals.values(end-n);
    n=i;
end
for i=1:(length(reverse_capture10.signals.values)-
(find(simout10.signals.values,1)-1));
    residual1.signals.values(i)=forward_capture10.signals.values(i);
end
saved_residuals10.signals.values=max(residual1.signals.values,saved_
residuals10.signals.values);
save('component_limit_residual11.mat','saved_residuals10')
%%For the servo signal - not commented as duplicate to above
for
i=find(simout11.signals.values,1):length(reverse_capture11.signals.v
alues);
    reverse_capture11.signals.values(i)=0;
end
n=0;
for i=1:length(reverse_capture11.signals.values);

residual1.signals.values(i)=reverse_capture11.signals.values(end-n);
    n=i;
end
for i=1:(length(reverse_capture11.signals.values)-
(find(simout11.signals.values,1)-1));
    residual1.signals.values(i)=forward_capture11.signals.values(i);
end
saved_residuals11.signals.values=max(residual1.signals.values,saved_
residuals11.signals.values);
save('component_limit_residual12.mat','saved_residuals11')
```

The fault detection and isolation script follows:

```
%When weld data has been run through model and the residual limits
created
open('start_up_fault_fc1_2_4')
sim('start_up_fault_fc1_2_4')

%Fault Isolation - Logic to detect which fault has been triggered
if
(((not(isempty(find(position_fault.signals(1,4).values(:,1),1)))&&no
t(isempty(find(position_fault1.signals(1,4).values(:,1),1)))&&...

not(isempty(find(position_fault2.signals(1,4).values(:,1),1)))&&not(
isempty(find(position_fault8.signals(1,4).values(:,1),1)))&&...

not(isempty(find(position_fault9.signals(1,4).values(:,1),1)))&&not(
isempty(find(position_fault10.signals(1,4).values(:,1),1)))&&...

not(isempty(find(position_fault3.signals(1,4).values(:,1),1)))&&not(
isempty(find(position_fault4.signals(1,4).values(:,1),1)))&&...

not(isempty(find(position_fault11.signals(1,4).values(:,1),1)))&&not
(isempty(find(position_fault7.signals(1,4).values(:,1),1))))==1)...

&&((isempty(find(position_fault5.signals(1,4).values(:,1),1))&&isemp
ty(find(position_fault6.signals(1,4).values(:,1),1))==1)))
    disp('Fault Case 1: Check HSM')%Outputs fault case 1 information
elseif
((not(isempty(find(position_fault1.signals(1,4).values(:,1),1))==1)&
&...

(isempty(find(position_fault.signals(1,4).values(:,1),1))&&...

isempty(find(position_fault2.signals(1,4).values(:,1),1))&&isempty(f
ind(position_fault8.signals(1,4).values(:,1),1))&&...

isempty(find(position_fault9.signals(1,4).values(:,1),1))&&isempty(f
ind(position_fault10.signals(1,4).values(:,1),1))&&...

isempty(find(position_fault3.signals(1,4).values(:,1),1))&&isempty(f
ind(position_fault4.signals(1,4).values(:,1),1))&&...

isempty(find(position_fault5.signals(1,4).values(:,1),1))&&isempty(f
ind(position_fault6.signals(1,4).values(:,1),1))&&...

isempty(find(position_fault11.signals(1,4).values(:,1),1))&&isempty(
find(position_fault7.signals(1,4).values(:,1),1)))==1))
    disp('Fault Case 2: Valve instabilities')%Outputs fault case 2
information
elseif
(((not(isempty(find(position_fault.signals(1,4).values(:,1),1)))&&no
t(isempty(find(position_fault8.signals(1,4).values(:,1),1)))==1))&&.
..

(isempty(find(position_fault1.signals(1,4).values(:,1),1))&&isempty(
find(position_fault2.signals(1,4).values(:,1),1))==1))
    disp('Fault Case 3: Check Wiring Connections')%Outputs fault
case 3 information
elseif not(isempty(find(spike_fault.signals(1,3).values,1)))==1
    disp('Fault Case 4: Electronics Failure')%Outputs fault case 4
information
```

```
end
```

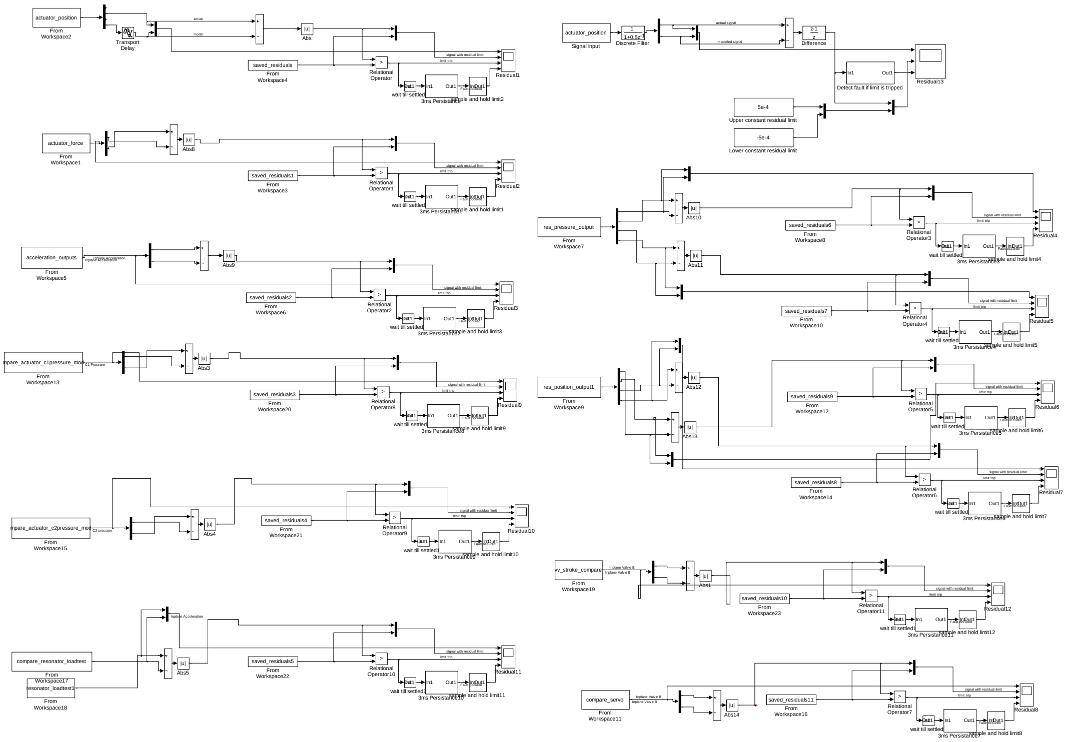

Figure 117 - Fault detection/isolation model

Appendix 7 – Fault Case 1 Further Results

This appendix shows the remaining fault case 1 results with discussion from chapter 6, section 6.3.1.

Fault case 1 was the start-up oscillation; Figure 118 shows the modelled vs. actual in-plane force signal, along with the residual/fault analysis. The adaptive residual limit is breached at the start of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

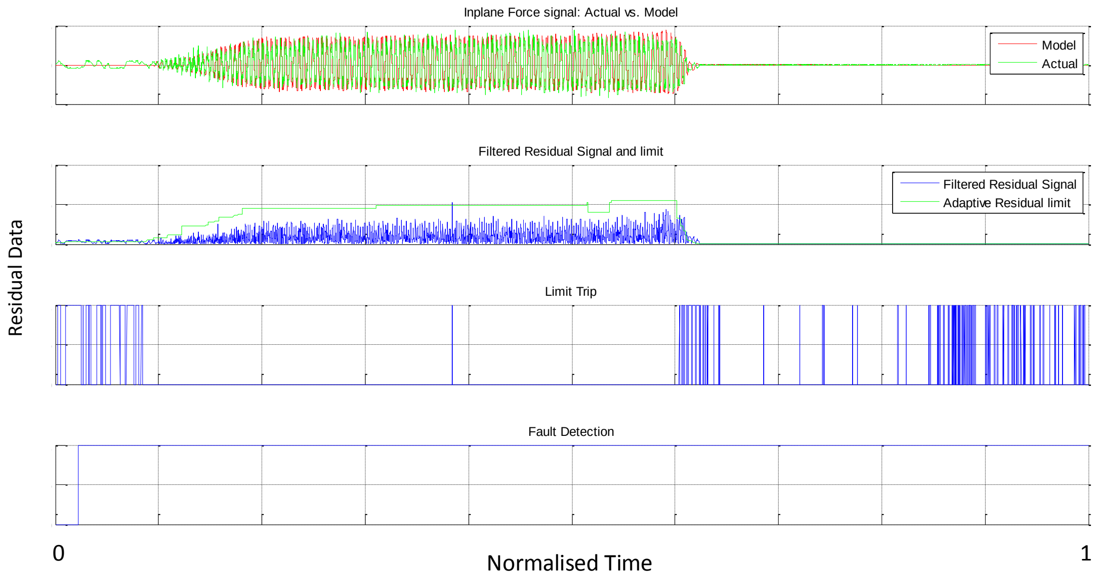

Figure 118 - Fault case 1: Actuator force. Fault detection with the residual generation method (fault)

Figure 119 shows the modelled vs. actual in-plane acceleration signal, along with the residual/fault analysis. The adaptive residual limit is breached at the start of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

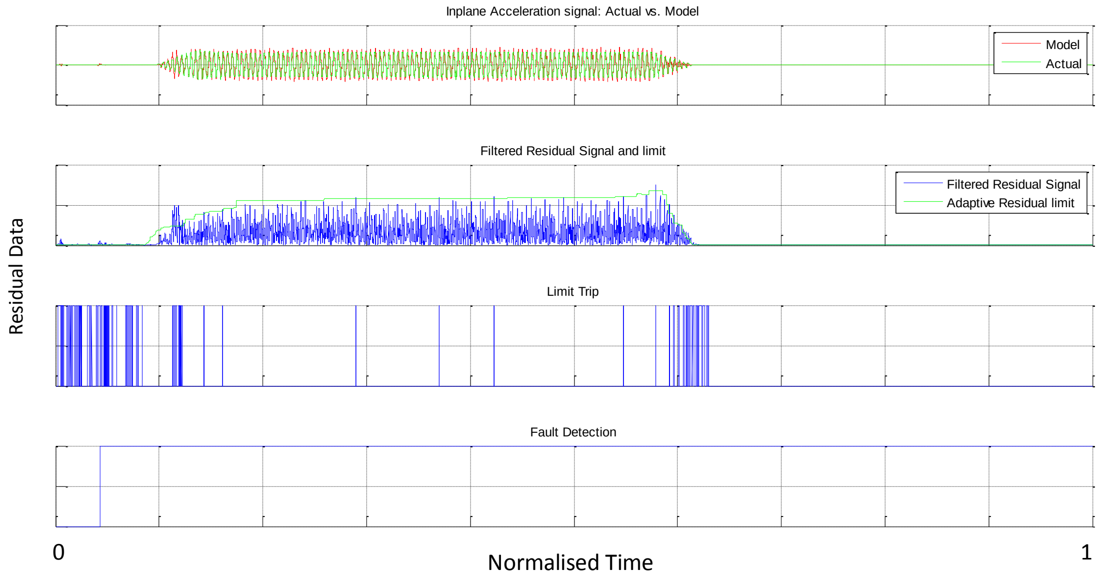

Figure 119 - Fault case 1: In-plane Acceleration. Fault detection with the residual generation method (fault)

Figure 120 shows the modelled vs. actual in-plane actuator C1 pressure signal, along with the residual/fault analysis. The adaptive residual limit is breached at the start of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

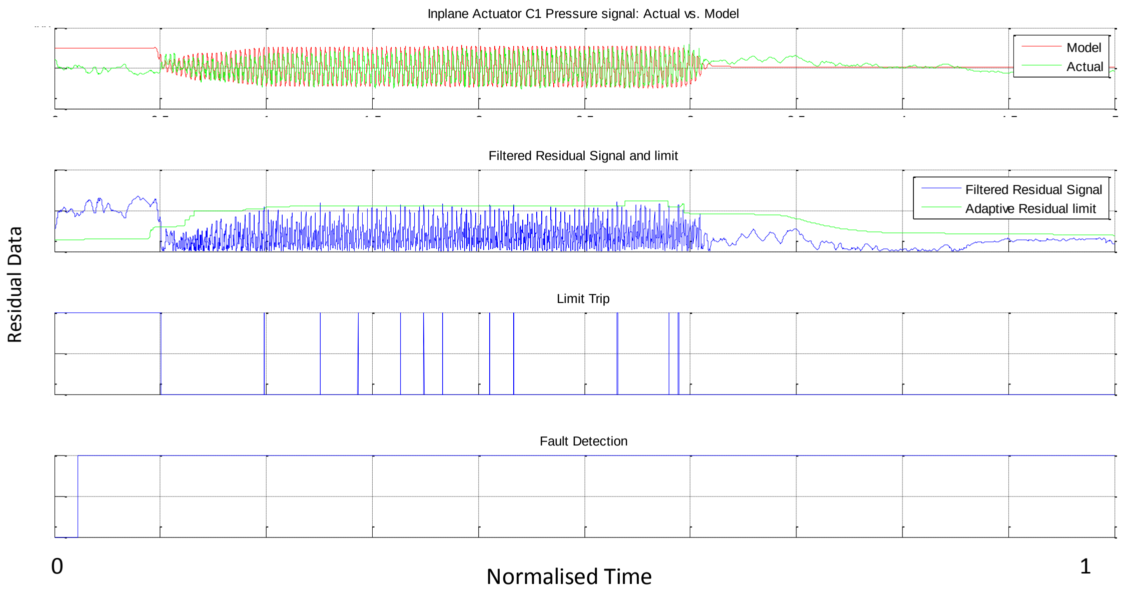

Figure 120 - Fault case 1: In-plane Actuator C1 Pressure. Fault detection with the residual generation method (fault)

Figure 121 shows the modelled vs. actual Resonator Load signal, along with the residual/fault analysis. The adaptive residual limit is breached at the start of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

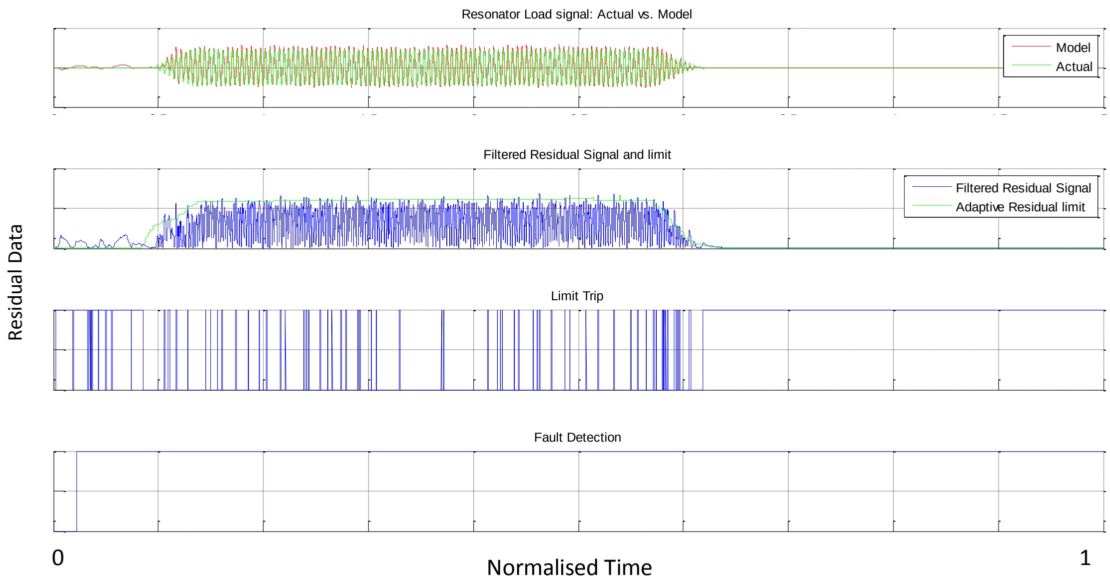

Figure 121 - Fault case 1: Resonator Load. Fault detection with the residual generation method (fault)

Figure 122 shows the modelled vs. actual Resonator Pressure C1 signal, along with the residual/fault analysis. The adaptive residual limit is breached at the start of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

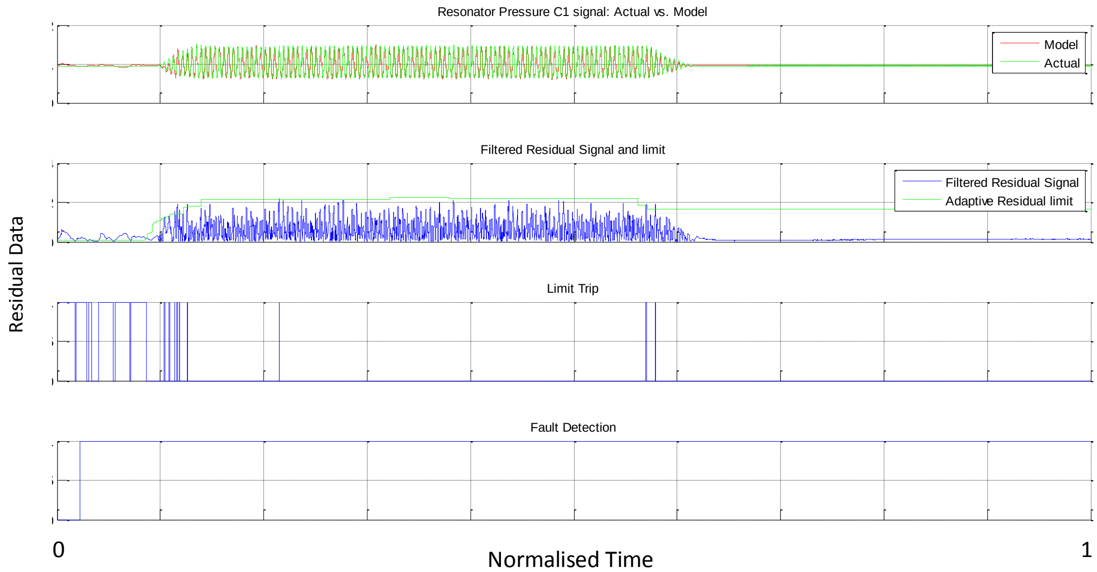

Figure 122 - Fault case 1: Resonator pressure C1. Fault detection with the residual generation method (fault)

Figure 123 shows the modelled vs. actual Resonator Pressure C2 signal, along with the residual/fault analysis. The adaptive residual limit is breached at the start of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

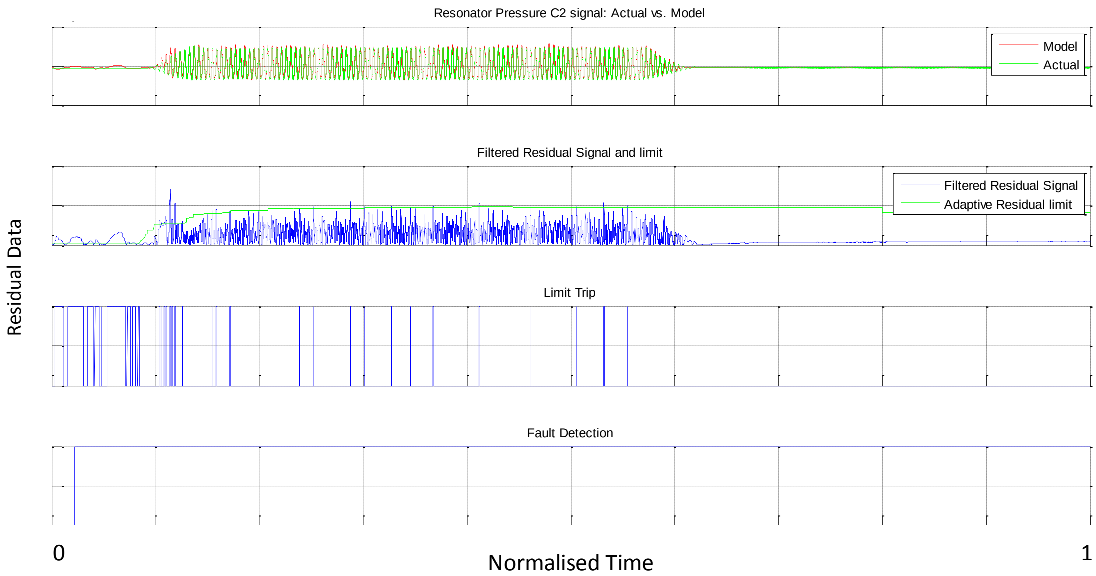

Figure 123 - Fault case 1: Resonator pressure C2. Fault detection with the residual generation method (fault)

Figure 124 shows the modelled vs. actual Resonator position C1 signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

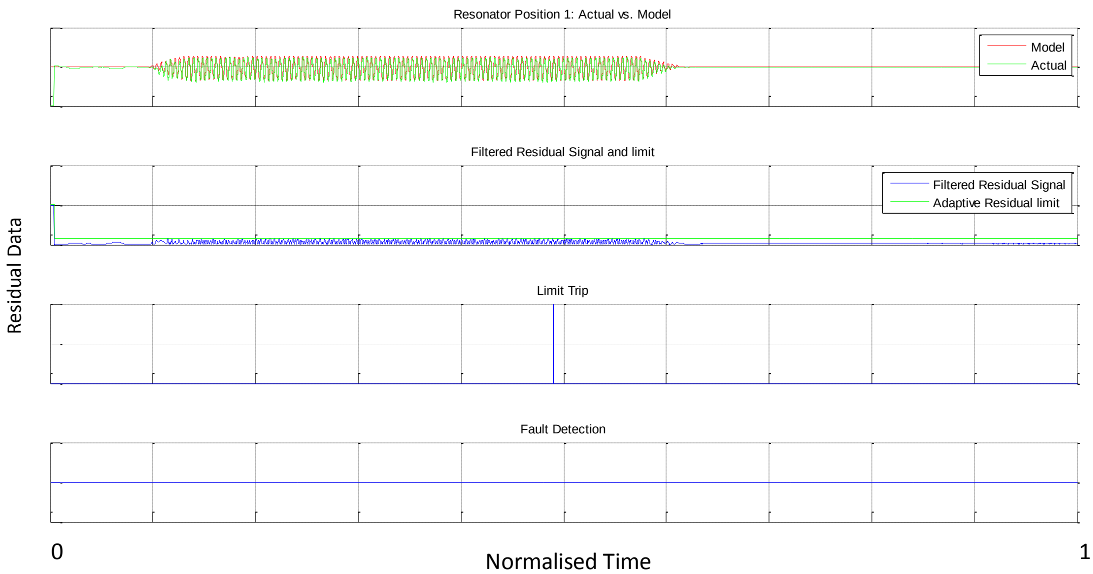

Figure 124 - Fault case 1: Resonator position C1. Fault detection with the residual generation method (fault)

Figure 125 shows the modelled vs. actual Resonator position C2 signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

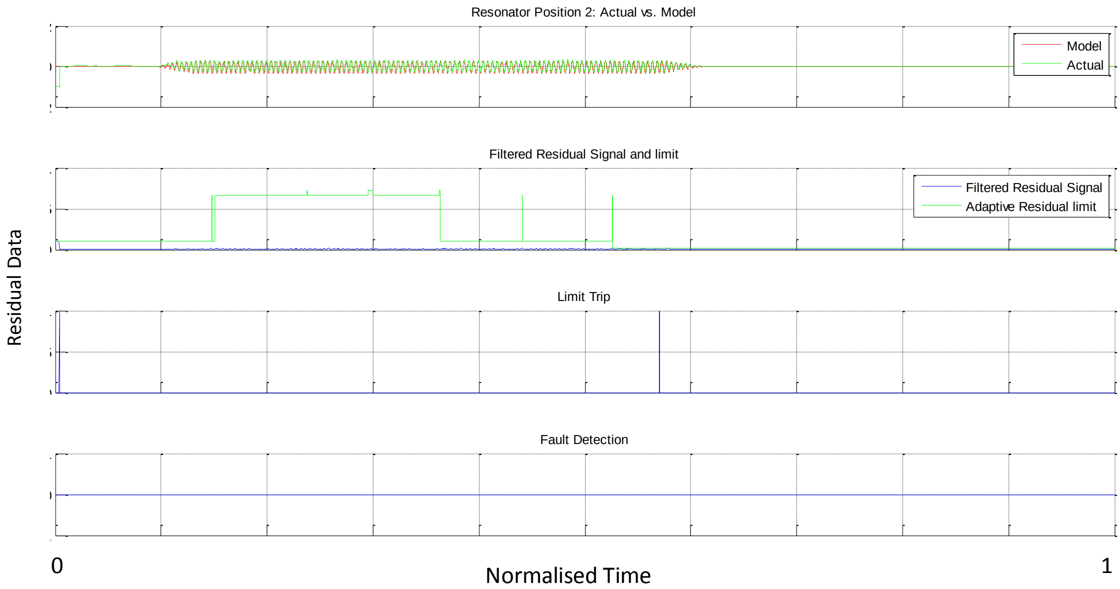

Figure 125 - Fault case 1: Resonator position C2. Fault detection with the residual generation method (fault)

Figure 126 shows the modelled vs. actual in-plane stroke displacement signal, along with the residual/fault analysis. The adaptive residual limit is breached at the start of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

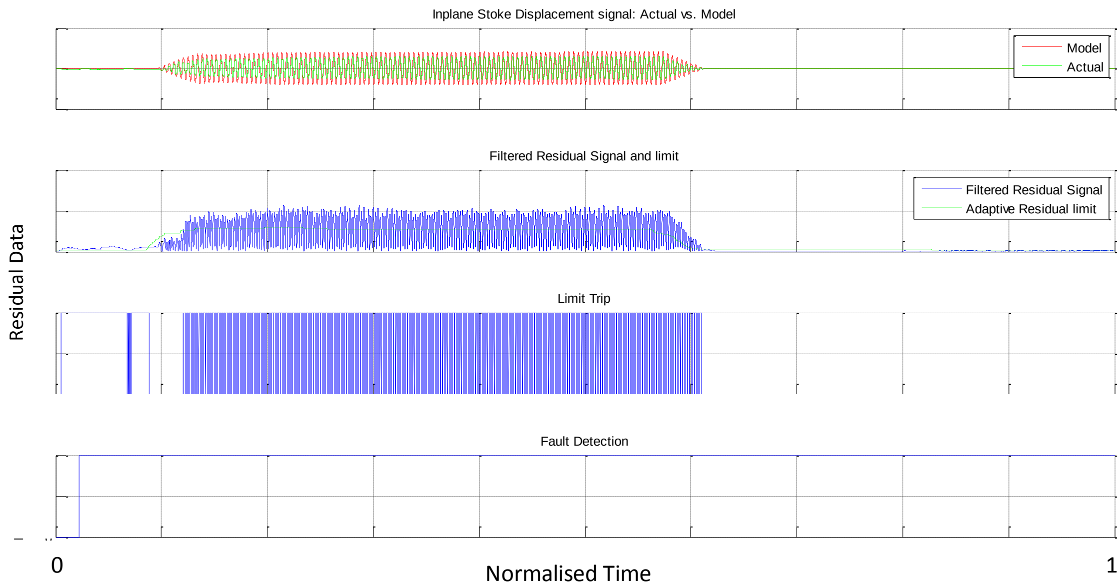

Figure 126 - Fault case 1: In-plane stroke displacement. Fault detection with the residual generation method (fault)

Figure 127 shows the modelled vs. actual in-plane servo signal, along with the residual/fault analysis. The adaptive residual limit is breached at the start of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

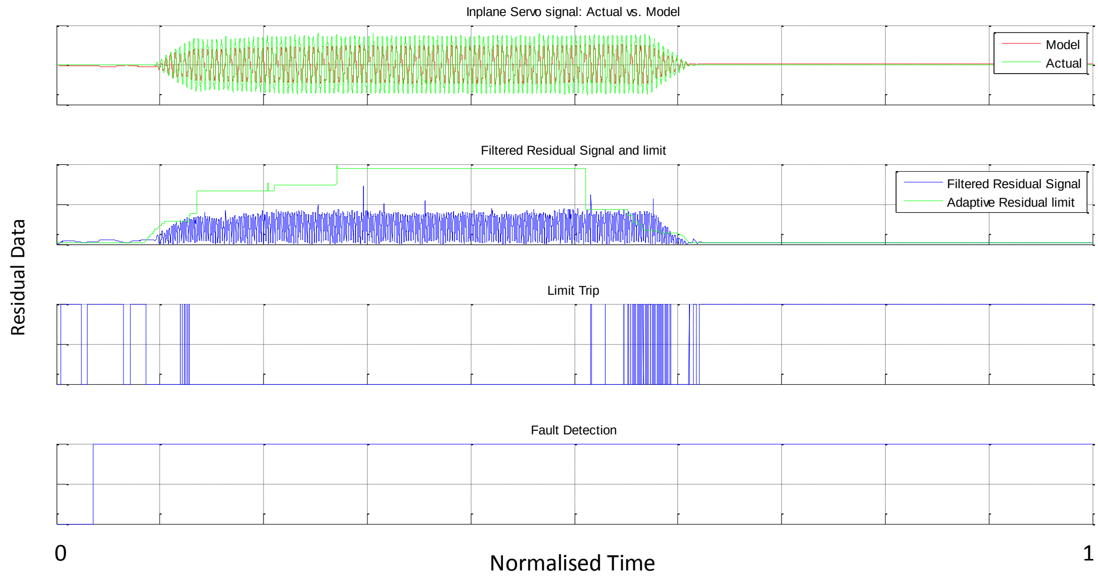

Figure 127 - Fault case 1: In-plane servo. Fault detection with the residual generation method (fault)

Fault case 1: fault detection summary chart:

Residual	Fault analysis
Actuator Position	Tripped
In-plane Force	Tripped
In-plane Acceleration	Tripped
Actuator C1 Pressure	Tripped
Actuator C2 Pressure	Tripped
Resonator Load	Tripped
Resonator C1 Pressure	Tripped
Resonator C2 Pressure	Tripped
Resonator C1 Position	Not Tripped
Resonator C2 Position	Not Tripped
In-plane Stroke Displacement	Tripped
In-plane Servo	Tripped

Table 10 - Fault Case 1: Signal Analysis

Model output: “Check Hydraulic Service Manifold”.

Appendix 8 – Fault Case 2 Further Results

This appendix shows the remaining fault case 2 results with discussion from chapter 6, section 6.3.2.

Fault case 2 was the force holding oscillation. Figure 128 shows the modelled vs. actual in-plane position signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

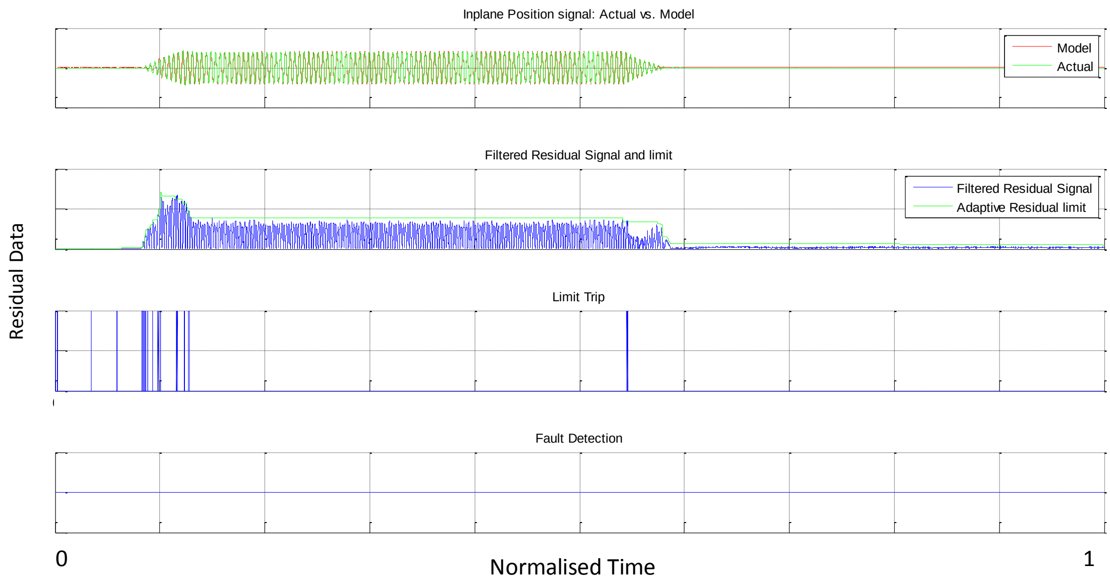

Figure 128 - Fault case 2: In-plane position. Fault detection with the residual generation method (fault)

Figure 129 shows the modelled vs. actual in-plane force signal, along with the residual/fault analysis. The adaptive residual limit is breached at the end of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

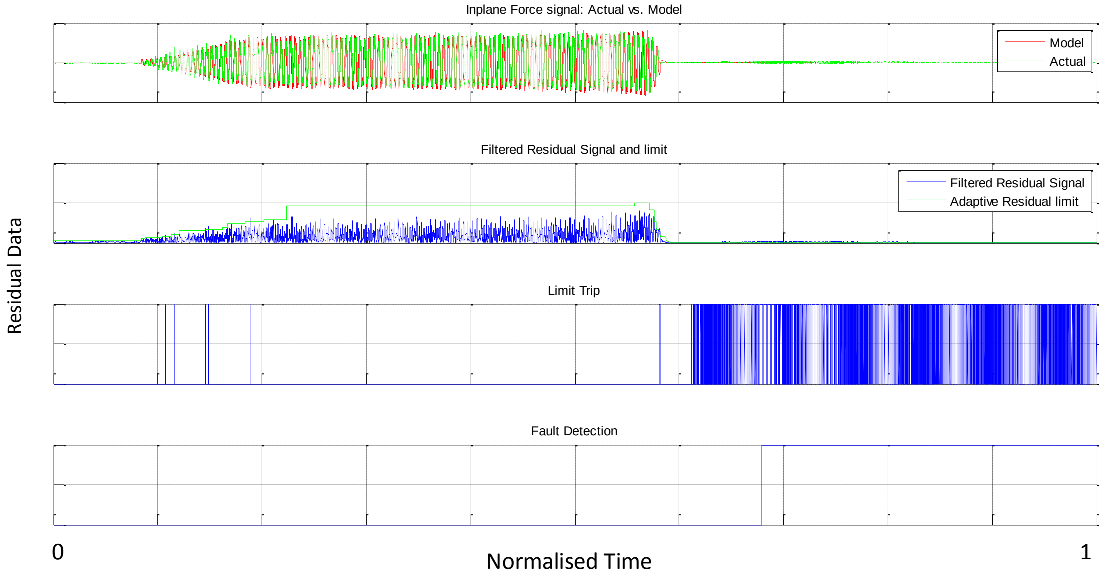

Figure 129 - Fault case 2: In-plane force. Fault detection with the residual generation method (fault)

Figure 130 shows the modelled vs. actual in-plane acceleration signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

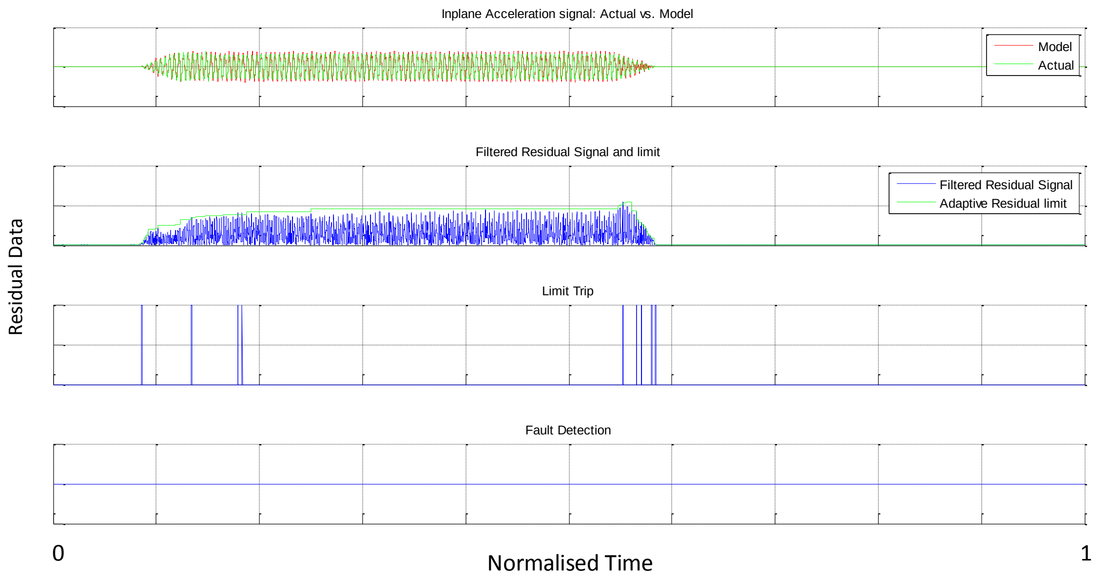

Figure 130 - Fault case 2: In-plane acceleration. Fault detection with the residual generation method (fault)

Figure 131 shows the modelled vs. actual actuator C1 pressure signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

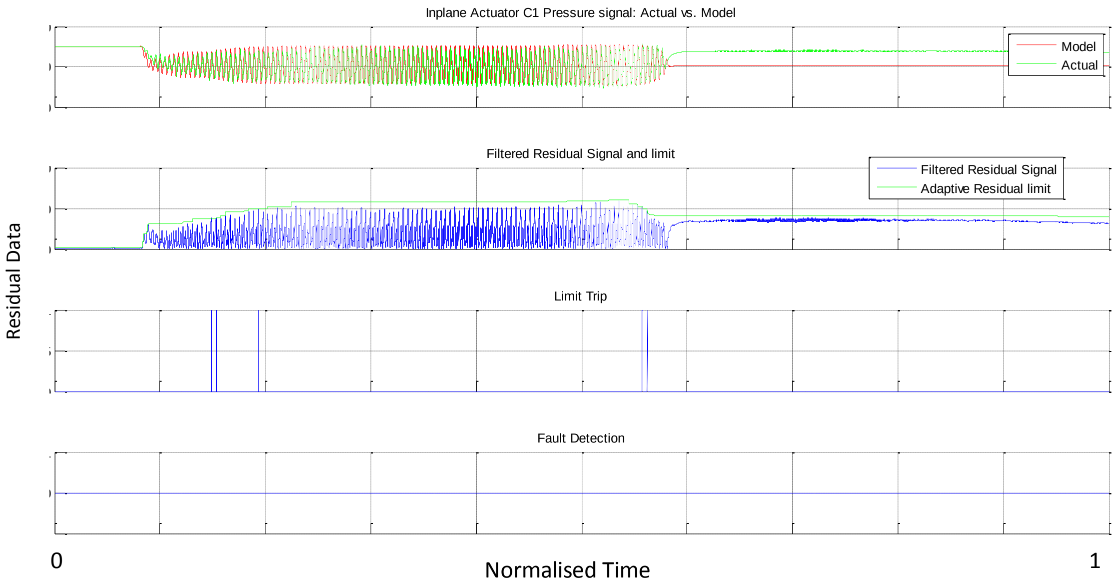

Figure 131 - Fault case 2: In-plane actuator C1 Pressure. Fault detection with the residual generation method (fault)

Figure 132 shows the modelled vs. actual in-plane actuator C2 pressure signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

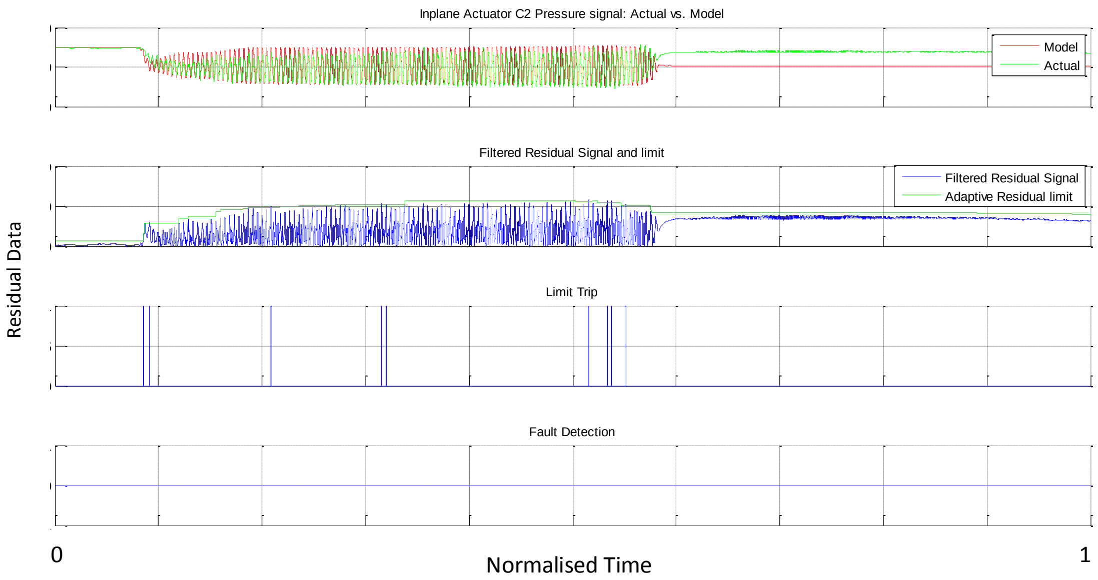

Figure 132 - Fault case 2: In-plane actuator C2 Pressure. Fault detection with the residual generation method (fault)

Figure 133 shows the modelled vs. actual Resonator load signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

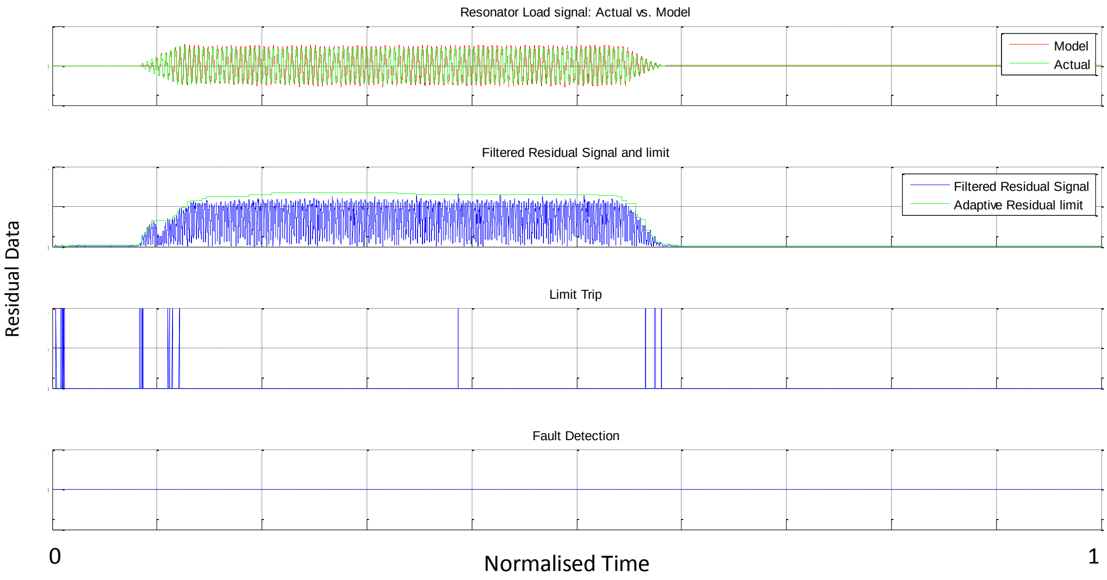

Figure 133 - Fault case 2: In-plane resonator load. Fault detection with the residual generation method (fault)

Figure 134 shows the modelled vs. actual resonator C1 pressure signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

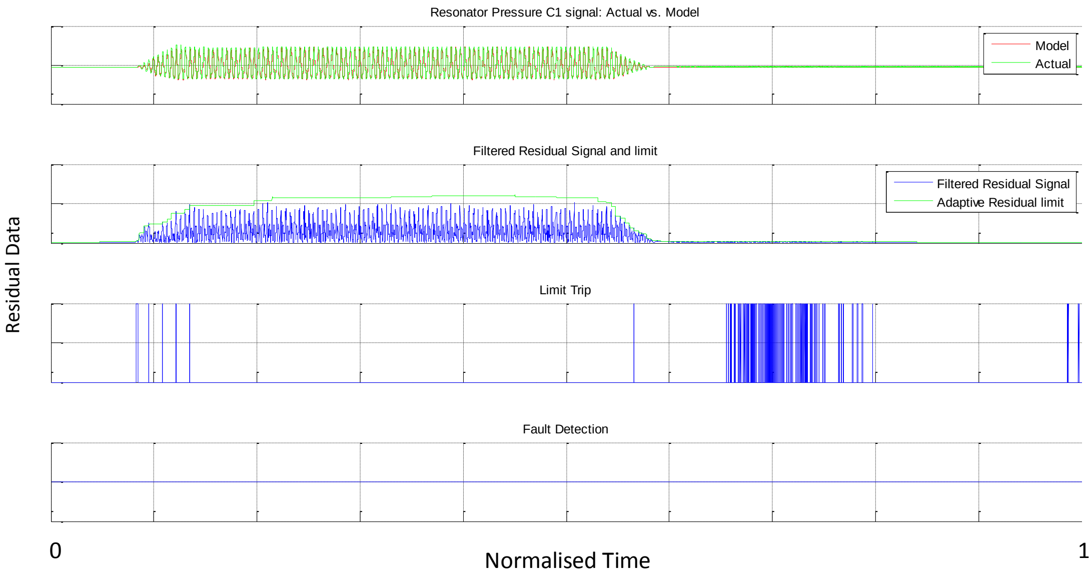

Figure 134 - Fault case 2: Resonator pressure C1. Fault detection with the residual generation method (fault)

Figure 135 shows the modelled vs. actual resonator C2 pressure signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

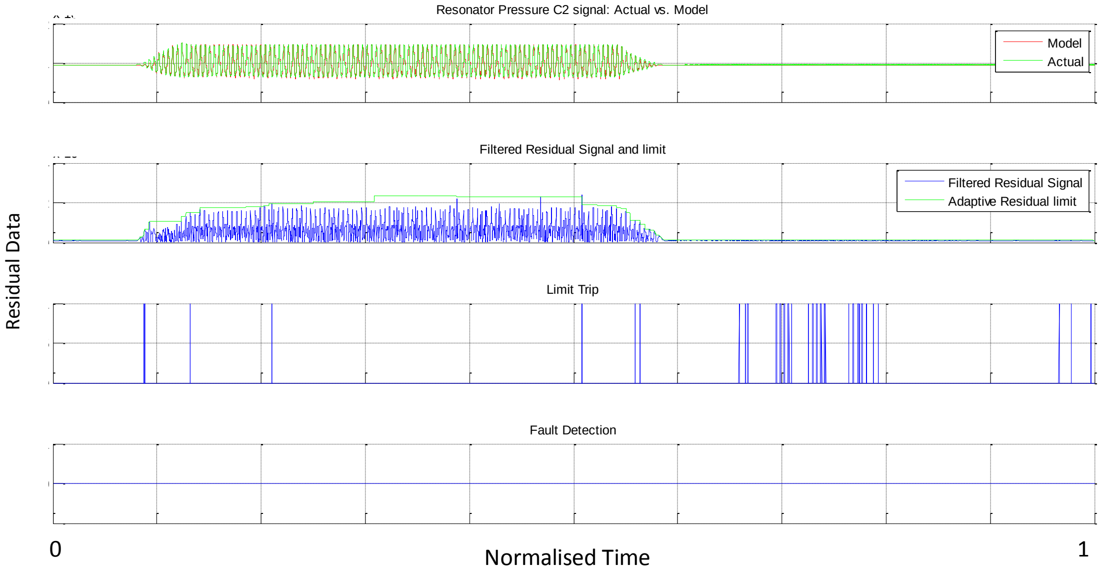

Figure 135 - Fault case 2: Resonator pressure C2. Fault detection with the residual generation method (fault)

Figure 136 shows the modelled vs. actual resonator position C1 signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

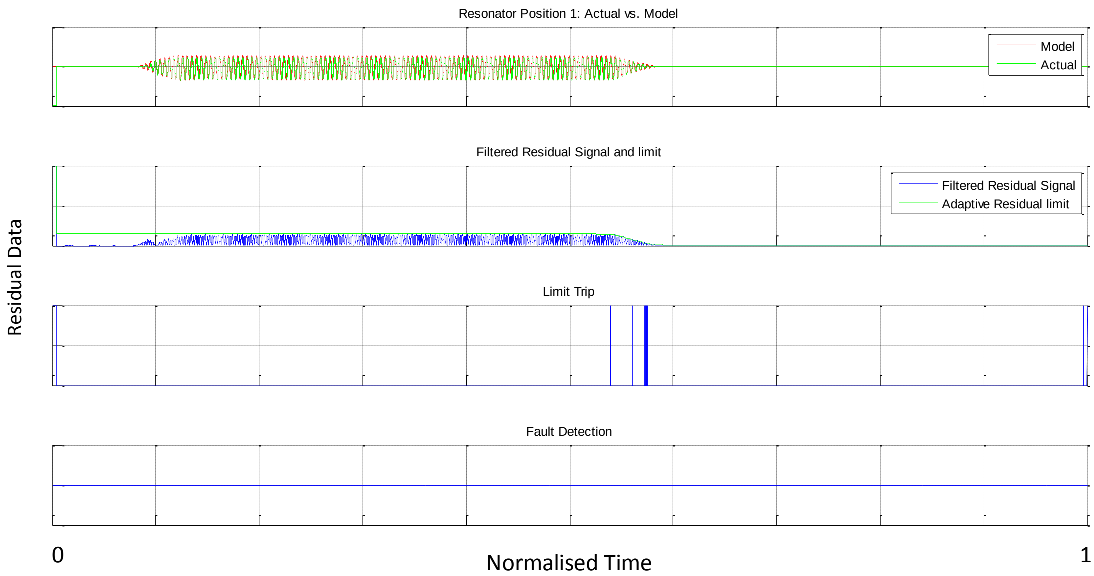

Figure 136 - Fault case 2: Resonator position C1. Fault detection with the residual generation method (fault)

Figure 137 shows the modelled vs. actual resonator position C2 signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

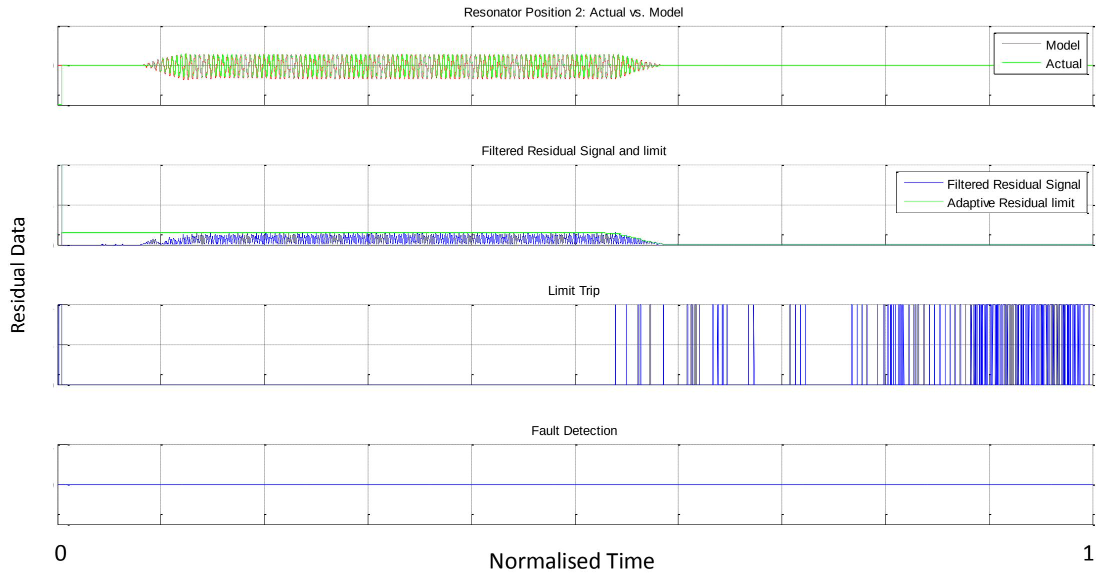

Figure 137 - Fault case 2: Resonator position C2. Fault detection with the residual generation method (fault)

Figure 138 shows the modelled vs. actual in-plane stroke displacement signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

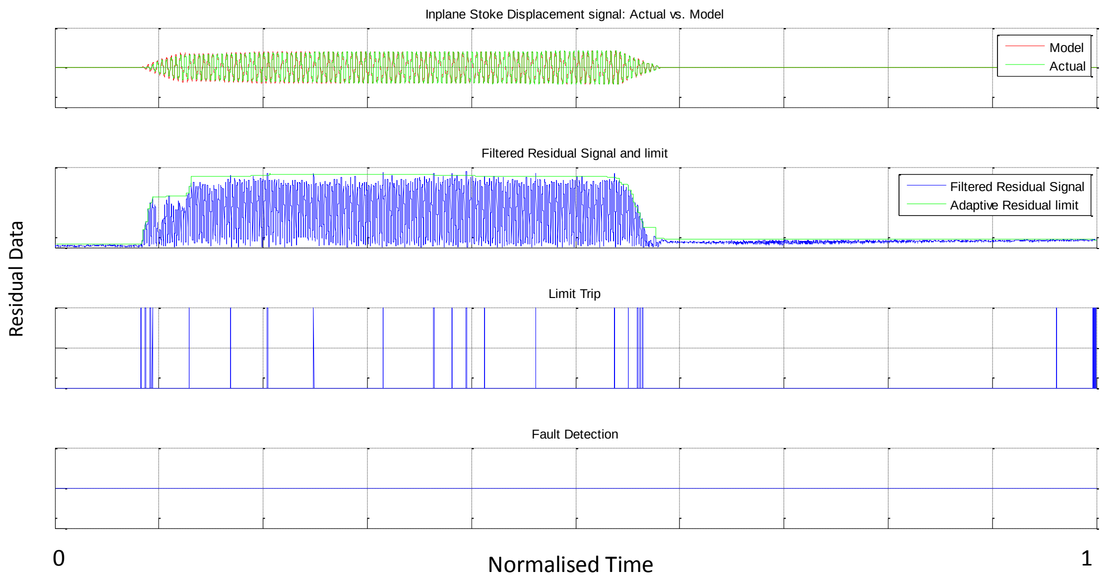

Figure 138 - Fault case 2: In-plane stroke displacement. Fault detection with the residual generation method (fault)

Figure 139 shows the modelled vs. actual in-plane servo signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

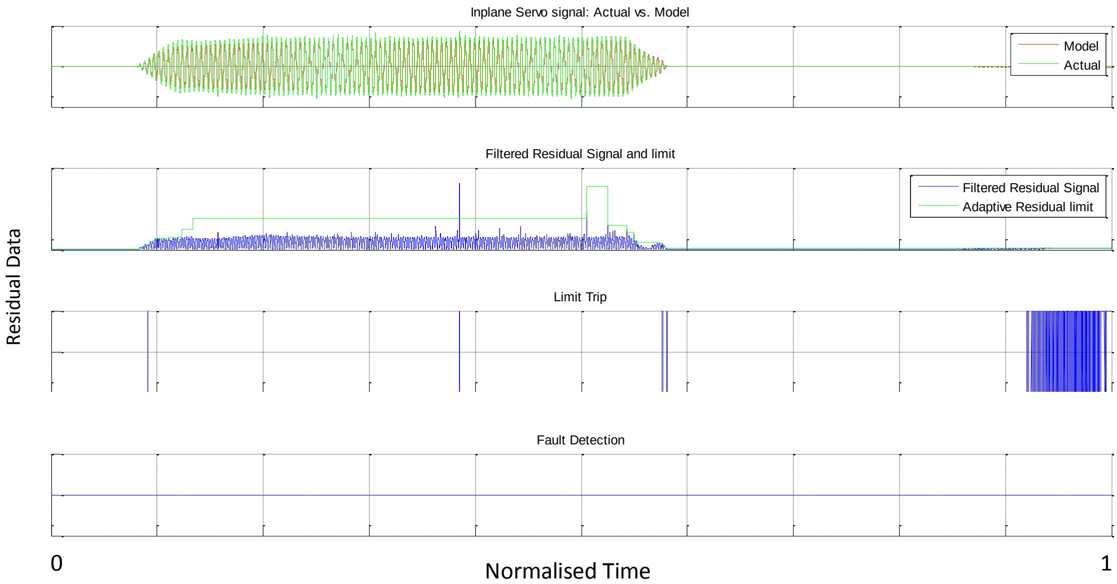

Figure 139 - Fault case 2: In-plane servo. Fault detection with the residual generation method (fault)

Fault case 2: fault detection summary chart:

Residual	Fault analysis
Actuator Position	Not Tripped
In-plane Force	Tripped
In-plane Acceleration	Not Tripped
Actuator C1 Pressure	Not Tripped
Actuator C2 Pressure	Not Tripped
Resonator Load	Not Tripped
Resonator C1 Pressure	Not Tripped
Resonator C2 Pressure	Not Tripped
Resonator C1 Position	Not Tripped
Resonator C2 Position	Not Tripped
In-plane Stroke Displacement	Not Tripped
In-plane Servo	Not Tripped

Table 11 - Fault Case 2: Signal Analysis

Model output: “Valve Instabilities”.

Appendix 9 – Fault Case 3 Further Results

This appendix shows the remaining fault case 3 results with discussion from chapter 6, section 6.3.3.

Fault case 3 was the position holding oscillation; Figure 140 shows the modelled vs. actual in-plane position signal, along with the residual/fault analysis. The adaptive residual limit is breached at the start of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

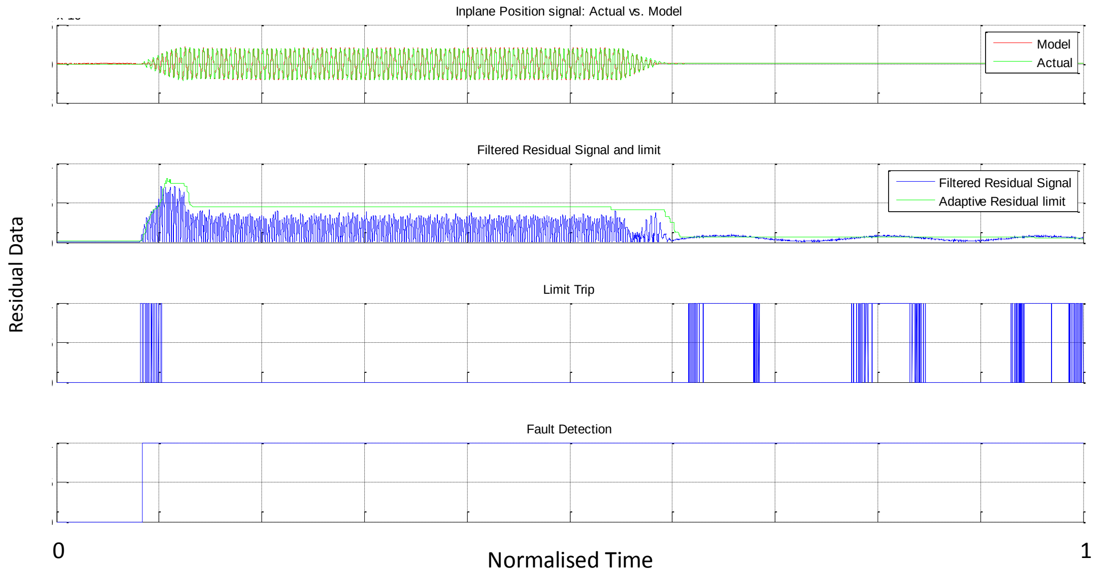

Figure 140 - Fault case 3: In-plane position. Fault detection with the residual generation method (fault)

Figure 141 shows the modelled vs. actual in-plane force signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

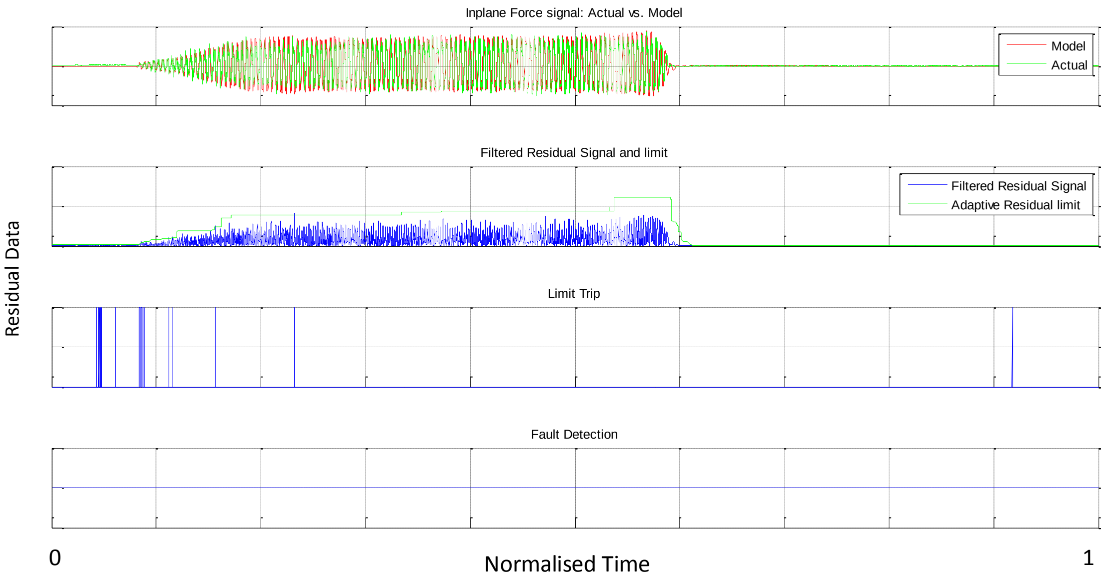

Figure 141 - Fault case 3: In-plane force. Fault detection with the residual generation method (fault)

Figure 142 shows the modelled vs. actual in-plane acceleration signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

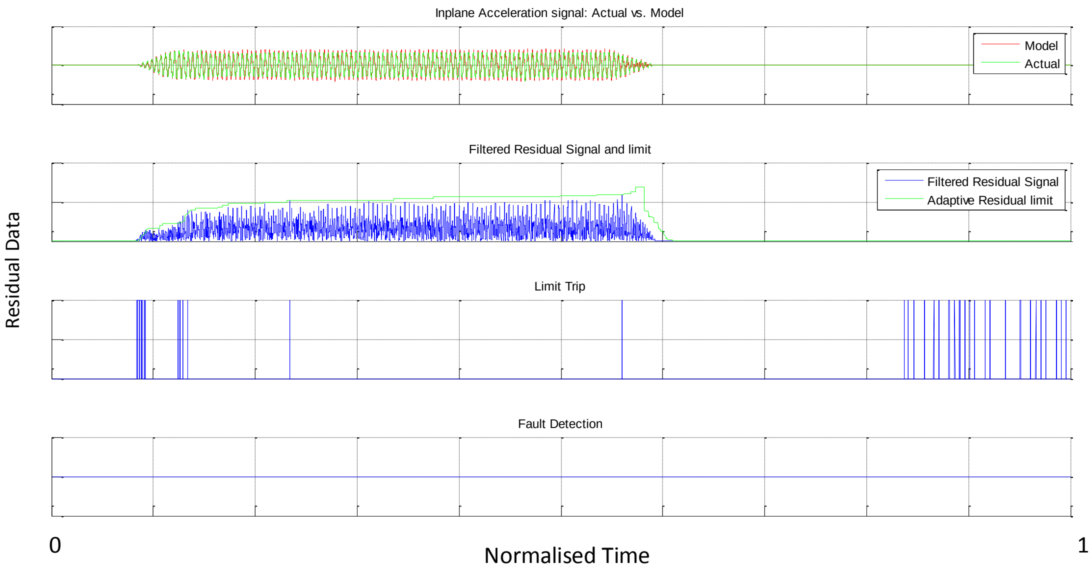

Figure 142 - Fault case 3: In-plane acceleration. Fault detection with the residual generation method (fault)

Figure 143 shows the modelled vs. actual in-plane actuator C1 pressure signal, along with the residual/fault analysis. The adaptive residual limit is breached at the start of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

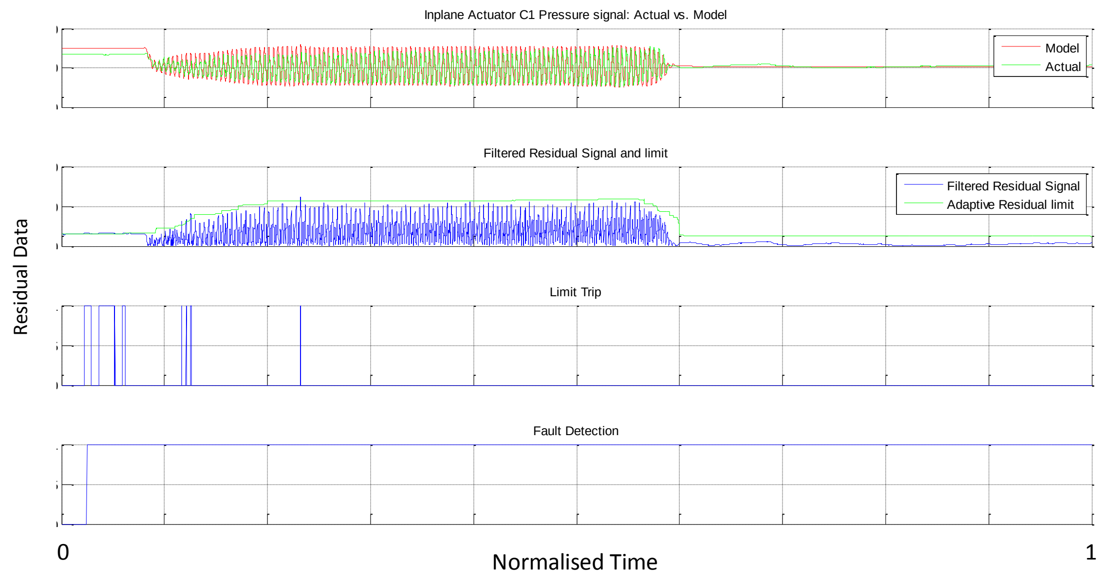

Figure 143 - Fault case 3: In-plane Actuator C1. Fault detection with the residual generation method (fault)

Figure 144 shows the modelled vs. actual in-plane actuator C2 pressure signal, along with the residual/fault analysis. The adaptive residual limit is breached at the start of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

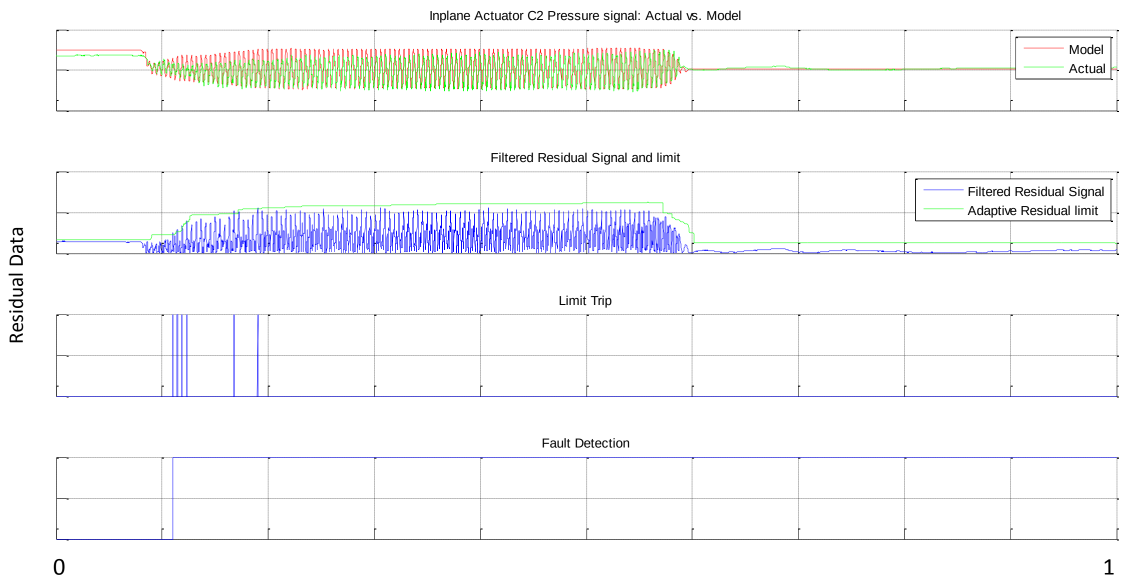

Figure 144 - Fault case 3: In-plane Actuator C2. Fault detection with the residual generation method (fault)

Figure 145 shows the modelled vs. actual Resonator load signal, along with the residual/fault analysis. The adaptive residual limit is breached at the start of the weld thus a fault is detected on this signal as indicated in the bottom part of the figure.

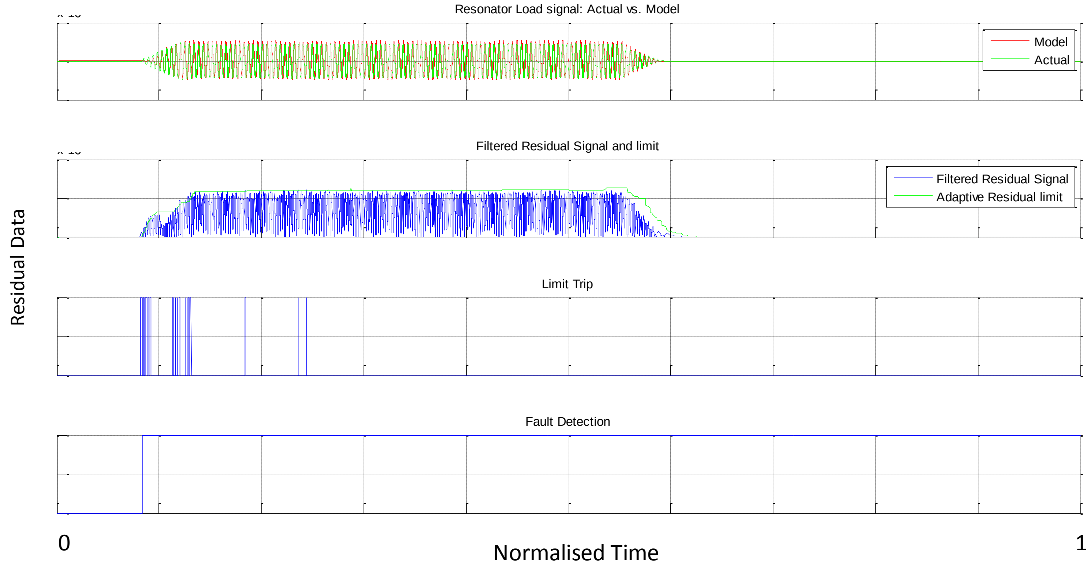

Figure 145 - Fault case 3: Resonator Load. Fault detection with the residual generation method (fault)

Figure 146 shows the modelled vs. actual Resonator Pressure C1 signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

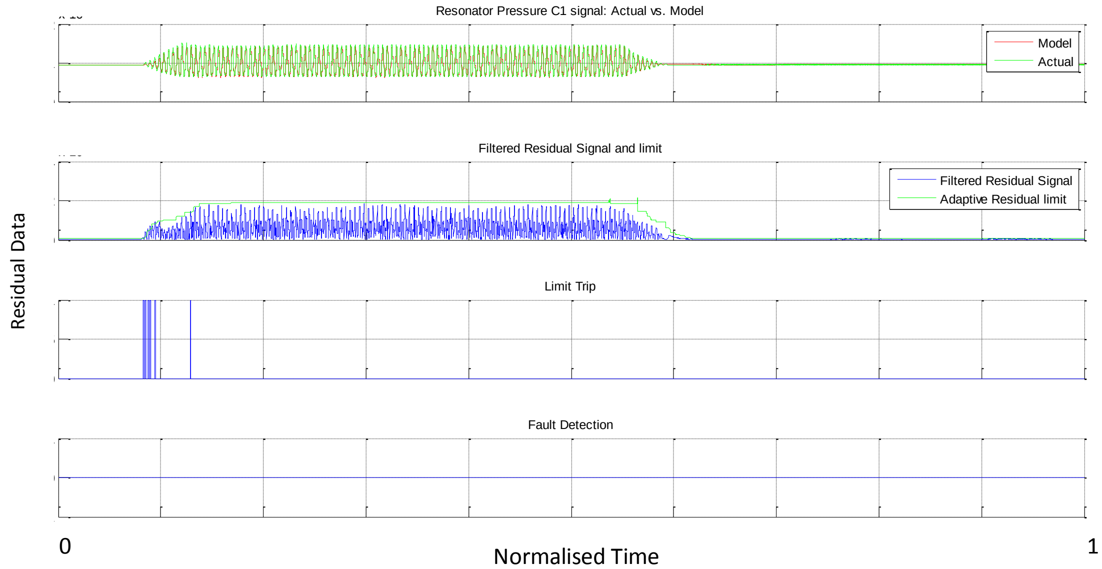

Figure 146 - Fault case 3: Resonator Pressure C1. Fault detection with the residual generation method (fault)

Figure 147 shows the modelled vs. actual Resonator Pressure C2 signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

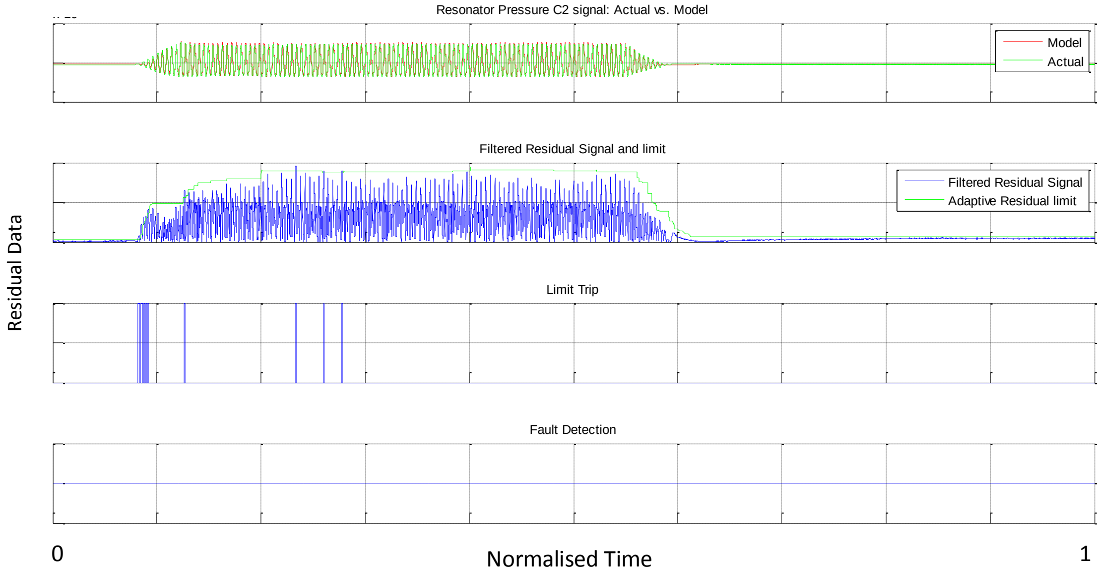

Figure 147 - Fault case 3: Resonator Pressure C2. Fault detection with the residual generation method (fault)

Figure 148 shows the modelled vs. actual Resonator position C1 signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

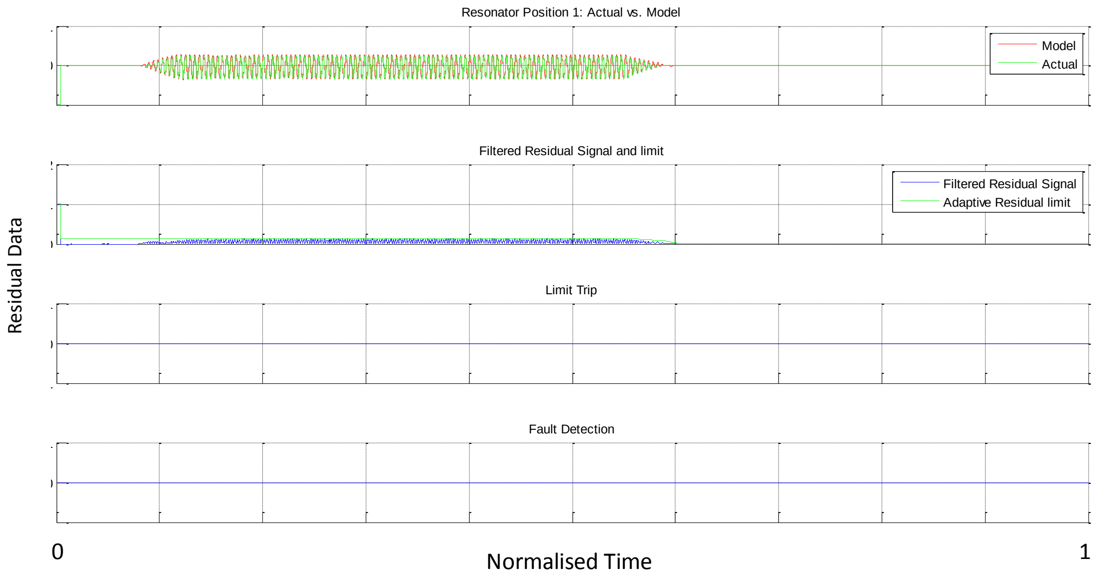

Figure 148 - Fault case 3: Resonator Position C1. Fault detection with the residual generation method (fault)

Figure 149 shows the modelled vs. actual Resonator position C2 signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

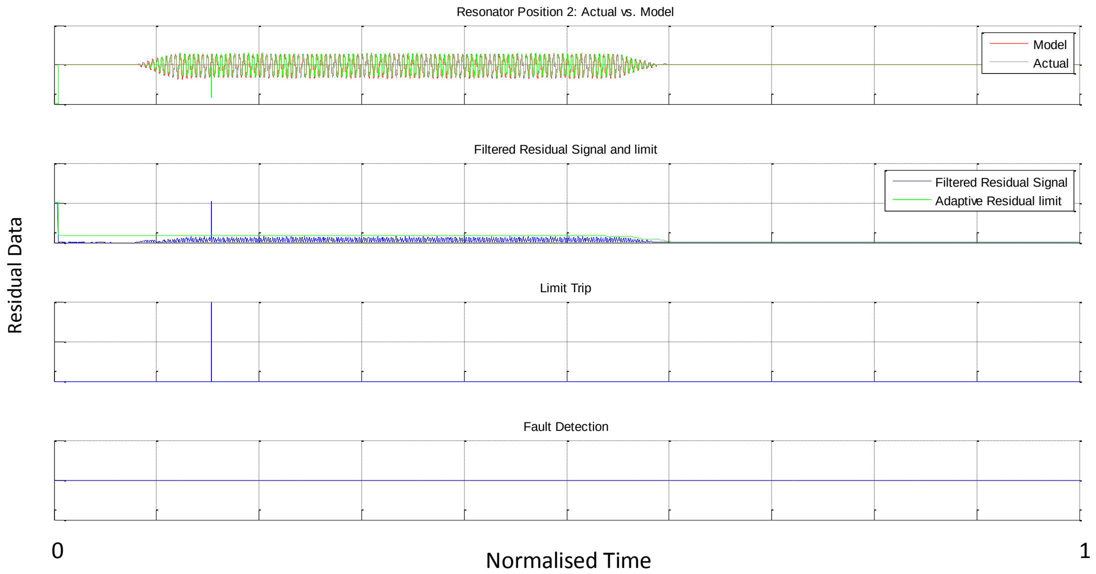

Figure 149 - Fault case 3: Resonator Position C2. Fault detection with the residual generation method (fault)

Figure 150 shows the modelled vs. actual in-plane displacement stroke signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

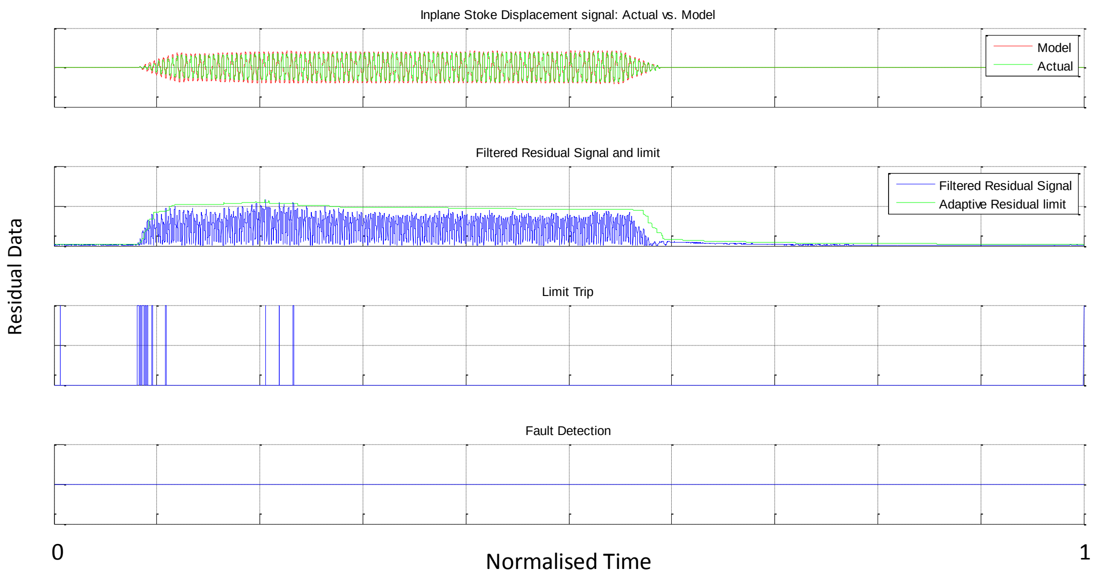

Figure 150 - Fault case 3: In-plane stroke displacement. Fault detection with the residual generation method (fault)

Figure 151 shows the modelled vs. actual in-plane servo signal, along with the residual/fault analysis. The adaptive residual limit is breached but not enough to create a fault detection alert, thus no fault is detected on this signal as indicated in the bottom part of the figure.

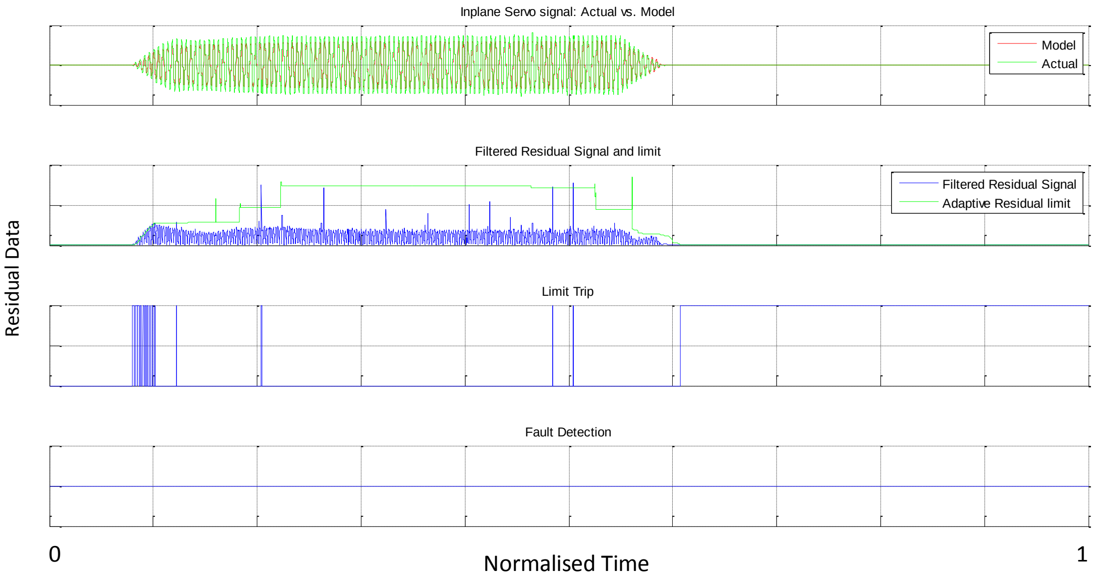

Figure 151 - Fault case 3: In-plane Servo. Fault detection with the residual generation method (fault)

Fault case 3: fault detection summary chart:

Residual	Fault analysis
Actuator Position	Tripped
In-plane Force	Not Tripped
In-plane Acceleration	Not Tripped
Actuator C1 Pressure	Tripped
Actuator C2 Pressure	Tripped
Resonator Load	Tripped
Resonator C1 Pressure	Not Tripped
Resonator C2 Pressure	Not Tripped
Resonator C1 Position	Not Tripped
Resonator C2 Position	Not Tripped
In-plane Stroke Displacement	Not Tripped
In-plane Servo	Not Tripped

Table 12 - Fault Case 3: Signal Analysis

Model output: “Electronics Failure”.

Appendix 10 – Interview Manuscripts

This appendix shows the interview manuscripts referenced in chapter 7.

DW & PG:
RR CRF workshop 26/9/201

What is your specific input to the LFW process?

operators calibrate maintenance calibration team power transducer
oil levels / bolts / air bags machine scheduled tracks tasks

What problems/opportunities do think there are with the LF60 machine? (Relating to user interactions?!)

valves - instabilities

Do you think the process is reliable? [explain]

No bespoke machine more or development machine i.e. not production standard

Based on what you have seen, what do you expect the benefits to be from Darrens work

catch things before potentially have out part

What are the key variables of the LFW process from your perspective involving people and the process?

operator knowledge - can't read in a book experience

Open question, is there anything else you have to say about the LFW process?

More Automated - brought up to date. [but still need human interaction on
- operators replied on more - certain aspects ie visual inspection for
writes technical instructions. dust]

Prompts

External influences – ISO, Regs, Standards

RR Quality System ~~RR~~ RPS 690

Internal influences – RR standards, specs

Validate/confirm hard systems element PDCA

DW & PG:
RR CRF workshop 26/9/201

What is your specific input to the LFW process?

Production support - offsets / calibration developing analysis system

SPC software & automated analysis. complex signal analysis.

What problems/opportunities do think there are with the LF60 machine? (Relating to user interactions?!)

Non flexible software - predicting position / offsets

Do you think the process is reliable? [explain]

Yes - when working trending is good CPK 30 V good

& No - cliff edge reaction, machine alteration, tooling.

Based on what you have seen, what do you expect the benefits to be from Darrens work

Catch instabilities before they occur - culture change to stop & do actions

What are the key variables of the LFW process from your perspective involving people and the process?

setting & datuming ie encoder set up it

Open question, is there anything else you have to say about the LFW process?

fundamentally good process complex but were starting to understand more

high production volumes

Prompts

External influences – ISO, Regs, Standards

SPC control with control charts, 5 or 6 spc rules, balanced rules & actions. Trust/faith in decision

Internal influences – RR standards, specs

RPS 690 welding spec MP27...

PWR, based on Component Approval packages. Quality assurance.

Validate/confirm hard systems element PDCA

F.A.I.R

live { FEMA machine
PFMEA process

DW & PG:
RR CRF workshop 26/9/201

What is your specific input to the LFW process?

Continuous improvement activities & fault diagnosis in breakdowns

tooling consulting & increasing knowledge & understanding. PDS Programme managing

What problems/opportunities do think there are with the LF60 machine? (Relating to user interactions?!)

Decisions come down to experience & gut feel

Do you think the process is reliable? [explain]

machine breakdowns but process is reliable even if parameters are slightly varied. CAP matrix of welds to test reliability of process. PWR process limits, limits in machine

Based on what you have seen, what do you expect the benefits to be from Darrens work

Improved process understanding, take reliance away from gut feel & experience capture instability & remember previous faults.

What are the key variables of the LFW process from your perspective involving people and the process?

Temperature of machine, strong correlation between output & temperature & time of welding ie morning - night then morning again.

Open question, is there anything else you have to say about the LFW process?

tasking with SPC - visualising outputs for people - graphs

Prompts

External influences – ISO, Regs, Standards

Internal influences – RR standards, specs

Validate/confirm hard systems element PDCA

process limits & PWR

CCR local

Process data card - manufacturing instructions - change control is FPA (or british) depending on which improvement method.

DW & PG:
RR CRF workshop 26/9/201

What is your specific input to the LFW process?

Production support using MPL - Post production, tripped limits WDR machine limits based on PWR, Calibration, Tuning, technical aspects of machine

What problems/opportunities do think there are with the LF60 machine? (Relating to user interactions?!)

Indicator for when something could go wrong

Do you think the process is reliable? [explain]

Annual calibration so reliable, increased volume for research machine would lead to faults.

Based on what you have seen, what do you expect the benefits to be from Darrens work

Prediction & where limits have missed it

What are the key variables of the LFW process from your perspective involving people and the process?

injure forge strokes, very data driven process, trip can take hours to take afternoon - running temp deviation - Night shift.

Open question, is there anything else you have to say about the LFW process?

More maintenance - predicting & detecting.

Prompts

External influences – ISO, Regs, Standards

JS3 document, delegating from technologies. filter faults, design authority can make changes

Internal influences – RR standards, specs

Audit ISO 9001 1401

US government audit NuCAP

Validate/confirm hard systems element PDCA

Sooner implement the better

DW & PG:
RR CRF workshop 26/9/201

What is your specific input to the LFW process?

fault diagnosis & service & repair, planned, proactive, breakdown

RR system Maximo. Alltell alerts based & number of cells on the machine

What problems/opportunities do think there are with the LF60 machine? (Relating to user interactions?!)

good maintenance period. complex & unique machine. OEM looked after it but when left knowledge dealt with him. Some knowledge still not documented, concise manuals.

Do you think the process is reliable? [explain]

Not Repeatable, but better than 3 or 4 years ago – continuous improvement cycle

Some bad designs, servicing, new changes, corrections not documented

Based on what you have seen, what do you expect the benefits to be from Darrens work

Predictive maintenance for tracking ~~systems~~ signals

If it not broke do we fix it. [LF20 LFT80 Inertia ~~[illegible]~~ Machine]

What are the key variables of the LFW process from your perspective involving people and the process?

Who's operating it – different levels of experience & knowledge.

→ wrong design i.e. clamping force not enough

Open question, is there anything else you have to say about the LFW process?

redesign after observing bad practice, installing incorrect procedures

Prompts

External influences – ISO, Regs, Standards

Machine Manual

maintained to manufacturer manual.

Internal influences – RR standards, specs

No

Validate/confirm hard systems element PDCA

DW & PG:
RR CRF workshop 26/9/201

What is your specific input to the LFW process?

operate & calibrate & maintenance the machine. Assist with routine maintenance O/S

fault finding during breakdown

What problems/opportunities do think there are with the LF60 machine? (Relating to user interactions?!)

Robustness / repeatability of calibration

reference blocks & setting gauges are used for measurements reading & calibrating

Do you think the process is reliable? [explain]

No 1999-2000 demonstration machine, now expected to do production parts

Based on what you have seen, what do you expect the benefits to be from Darrens work

Thinking work, background & research helped understanding. 250K+ scrap

cost saving.

What are the key variables of the LFW process from your perspective involving people and the process?

calibration & maintenance are key input & conflicting information.

- different outputs

Open question, is there anything else you have to say about the LFW process?

get inputs understood to make outputs reliable

- part data review -

Prompts

External influences – ISO, Regs, Standards

Details used for quality approval.

Dlink manufactured with a CFC certificate for conformance RPS 640

M.I. T.I SOP LOP

Internal influences – RR standards, specs

Validate/confirm hard systems element PDCA

/

DW & PG:
RR CRF workshop 26/9/201

What is your specific input to the LFW process?

Maintenance, fault finding & used to work on production OPs & Maint

What problems/opportunities do think there are with the LF60 machine? (Relating to user interactions?!)

Education, complex kit - No one has a good overall view. decision based on committee.
↑ years to take a good understanding. within apprentice trained,

Do you think the process is reliable? [explain]

reasonable for what it is (development machine). Specialists comment on its complexity.

Based on what you have seen, what do you expect the benefits to be from Darrens work

helps with diagnosis can save time & money   big decision to stop production
→ culture on machine - only change when need to.   Need risk review, i.e. encoder

What are the key variables of the LFW process from your perspective involving people and the process?

hydraulic oil & devices, Knowledge of the people, Calibre of people
*inline filtration unit

Open question, is there anything else you have to say about the LFW process?

Knowledge - added technical insight. Technical support

Prompts

External influences – ISO, Regs, Standards

Maximo - management tool
built in software package for maintenance & calibration

Internal influences – RR standards, specs

Validate/confirm hard systems element PDCA

* Experience of people

/

DW & PG:
RR CRF workshop 26/9/201

What is your specific input to the LFW process?

Operations manager H&S delivery

What problems/opportunities do think there are with the LF60 machine? (Relating to user interactions?!)

Predict ~~what~~ when breakdown

Do you think the process is reliable? [explain]

used to be 2, but now 5 or 6 reduced production

– production volume → see tony jones – machine availability & OEE

Based on what you have seen, what do you expect the benefits to be from Darrens work

Respect & been here a while so built up trust.

OPS & MAINT close OPS & LFW close

What are the key variables of the LFW process from your perspective involving people and the process?

Open question, is there anything else you have to say about the LFW process?

Visual outputs for prediction

clear picture of what they need to do & what action to take

Prompts

External influences – ISO, Regs, Standards

Near miss board, T cards,

5S, gold standard, 7 step investigation for instability.

Internal influences – RR standards, specs

deliver on time & right quality standard.

Validate/confirm hard systems element PDCA

DW & PG:
RR CRF workshop 26/9/201

What is your specific input to the LFW process?

NC team – Production support – Keep production going & SPC analysis
Weld deviation automation

What problems/opportunities do think there are with the LF60 machine? (Relating to user interactions?!)

Software due to limits – based on time therefore false alerts & downtime

Do you think the process is reliable? [explain]

Yes from SPC data high Cpk but without warning can go out of control.

Based on what you have seen, what do you expect the benefits to be from Darrens work

Difference between what happening & what expecting to happen. Predictable based on details & data

What are the key variables of the LFW process from your perspective involving people and the process?

Human interaction between different operators even though standard procedures
→ Improvement → All standard procedures to remove all variance.

Open question, is there anything else you have to say about the LFW process?

No.

Prompts

External influences – ISO, Regs, Standards

RPS 690 – welding spec – materials & geometry
calibration & maintenance out of date – won't run

Internal influences – RR standards, specs

NuCAP – need to be satisfied paperwork & documentation
batch cards & history cards and T.I all in place.

Validate/confirm hard systems element PDCA

Traceability tooling & calibration